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Review Article

The Effect of Electric Heavy Vehicles on Flexible Pavements in Australia: A Review

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Abstract

Decarbonisation of heavy vehicles to achieve net-zero greenhouse gas emissions, through the adoption of Zero-Emission Heavy Vehicle (ZEHV) technologies, inevitably influences vehicle typology and axle mass distribution. The additional weight of batteries used in ZEHV systems must be accommodated within existing vehicle mass limits. In Australia, the freight industry is advocating for a minimum one tonne increase in the allowable steer axle load to facilitate greater uptake of electric heavy vehicles. This desktop review investigates the potential effects of a one tonne increase in steer axle load on flexible pavements of both local roads and rural national highways. Currently, there is no nationally standardised methodology for assessing unacceptable pavement wear. This study compares several approaches and concludes that the use of mechanistic-empirical method with weigh-in-motion (WIM) data provides a more accurate assessment of pavement wear than analyses based solely on individual vehicle axles or total vehicle axle loads. The pavement wear analysis indicates that the steer axle contributes the greatest cumulative distress across all pavement types examined. Furthermore, the results show that a one-tonne increase in steer axle load would have a substantially greater impact on local roads- leading to an estimated 31.3% to 48.7% reduction in pavement life- compared with a 20.9% reduction in rural national highways.

Keywords

Zero Emission Heavy Vehicle, Decarbonisation, Mass Limit, Axle Load, Steer Axle, Pavement Wear

1. Introduction

Australia has a clear commitment to establishing a pathway for decarbonising heavy vehicles to achieve net-zero greenhouse gas (GHG) emissions by 2050 [1]. Potential technological solutions for the decarbonisation of heavy-duty vehicle sector include biofuels, battery-electric propulsion, hydrogen fuel systems and electric road technologies. These options are emerging technologies that may become economically viable under specific operating conditions and assumptions [2]. This study focuses specifically on battery-electric heavy vehicles.

The implementation of Zero-Emission Heavy Vehicle (ZEHV) technology inherently alters vehicle typology and distribution of loads between the steer and drive axles. The additional weight induced by ZEHV battery systems must be accommodated within existing vehicle design and regulatory frameworks. The increased battery load substantially increases axle loads, resulting in higher pavement stresses that accelerates structural deterioration and reduces pavement

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service life. Although ongoing technological advancements are expected to improve ZEHV efficiency, transitioning heavy vehicle fleets to ZEHV without corresponding adjustments to allocable load limits would inevitably reduce payload capacity. This reduction constrains feasible battery size and vehicle operating range, thereby diminishing commercial viability. Consequently, limitations on payload and load allowances may present significant economic barriers to the large-scale adoption of ZEHVs [1].

Globally, jurisdictions are revising policy frameworks to accommodate the transition toward heavy vehicle configurations, which may involve increasing allowable load limits and axle loads. These policy adjustments are often informed by evaluations of pavement performance and structural capacity to sustain additional loading stresses [3]. In contrast, responses within Australia have been heterogeneous, with state and territory jurisdictions adopting varied policy positions and regulatory measures to the challenges associated with increase vehicle mass and axle loads [1]. Australia's axle mass regulations are comparatively lower than major supplier economies such as United States and Europe. The current steer axle mass limit is 6.5 tonnes poses constraint on the deployment of larger electric truck models. In the short term, the Australian freight industry is advocating for a minimum one-tonne increase in the allowable steer axle to facilitate broader adoption of electric trucks [4-6].

Evidently, there is a knowledge gap in this subject with no known research to study the impact of electric heavy vehicles on flexible pavements in Australia. Furthermore, there is no unified approach to account accurately the level of imparted damage attributed to electric heavy vehicles on local roads and national rural highways. This review will provide a distinct contribution beyond existing Austroads reports referenced in this study.

The objective of this study is to investigate the effect of a 1-tonne increase in steer axle load on flexible pavements for local roads and rural national highways. In addition, an extensive review of the relevant literature is conducted to identify existing methods for quantifying pavement damage caused by electric heavy vehicles. The commonly used approaches for evaluating pavement damage are described, and their respective advantages and limitations are discussed. This provides a useful reference for practitioners seeking to assess pavement deterioration associated with increased axle loads from electric heavy vehicles.

2. Decarbonising Transport

Australia's adoption of electric vehicles (EVs) has lagged significantly behind that of other major economies, as illustrated in Figure 1. This slower uptake is largely attributed to the absence of strong government policies and consistent strategic messaging to promote EV adoption as a key measure for achieving national emission reduction targets [7, 8].

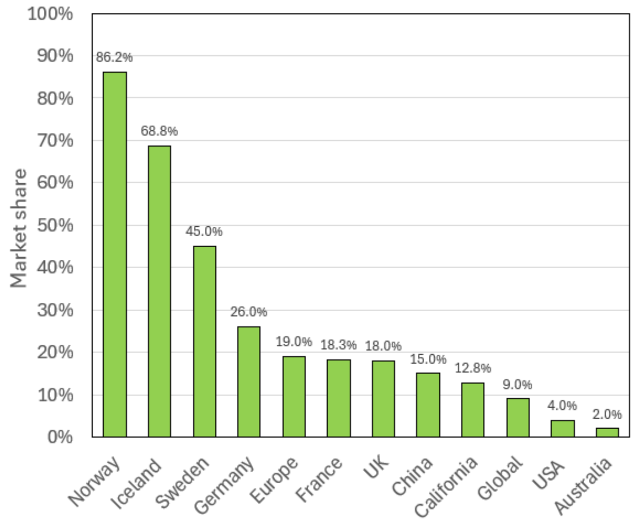

Figure 1. *Electric Vehicle Market Shares in 2021 (Data Source: Deloitte [6]).*

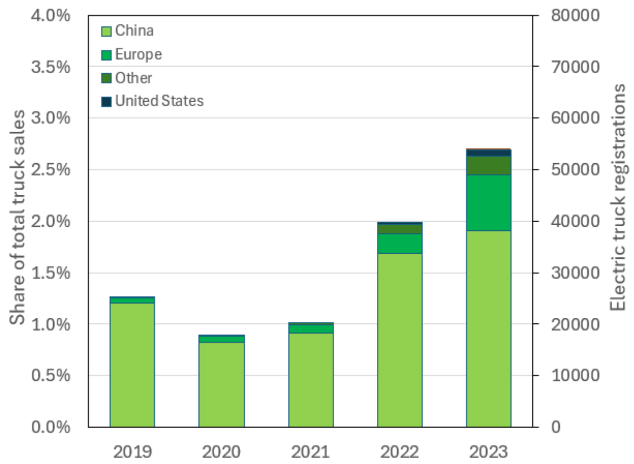

Figure 2. *Electric Truck Registrations and Sales by Regions (Data Source: IEA [9]).*

A closer examination of global electric truck market revels that China dominates, accounting for approximately 70% of worldwide sales in 2023. This leadership is attributed to a large customer base and high demand for such vehicles. Moreover, China has implemented battery-swapping system at charging stations, allowing vehicles to replace depleted batteries with a fully charged ones within minutes, rather than waiting several hours for a conventional charge. This arrangement effectively alleviates range anxiety, providing an experience comparable to refuelling at a petrol station. European Union countries have also seen a significant increase in electric truck adoption, with sales tripling within a single year. In the United States, a similar upward trend occurred in 2023, though total sales reached only 1200 units, representing 2% of the global market, as shown in Figure 2. Australia accounts for less than 1% of global heavy vehicle sales, placing it at risk of reduced access to the latest electric truck technologies unless stringent emission standards are adopted [10].

In 2024, the European Parliament voted to mandate a phased reduction of CO_2 emissions from trucks and buses, targeting a 90% reduction between 2030 and 2040. In Australia, the largest contributors to transport-related GHG emissions are passenger cars and light commercial vehicles as shown in Figure 3. These two sectors are therefor particularly well-suited to electric vehicle adoption and should be prioritised within the National Electric Vehicle Strategy. Notably, transport emissions in Australia account for approximately 19% of the total national emissions, with the road freight sector contributing 38% of this total [5]. In comparison, heavy-duty vehicles in the United States generate roughly 25% of the transport-related GHG emissions, despite representing only a small fraction (6%) of the total vehicle fleet [12].

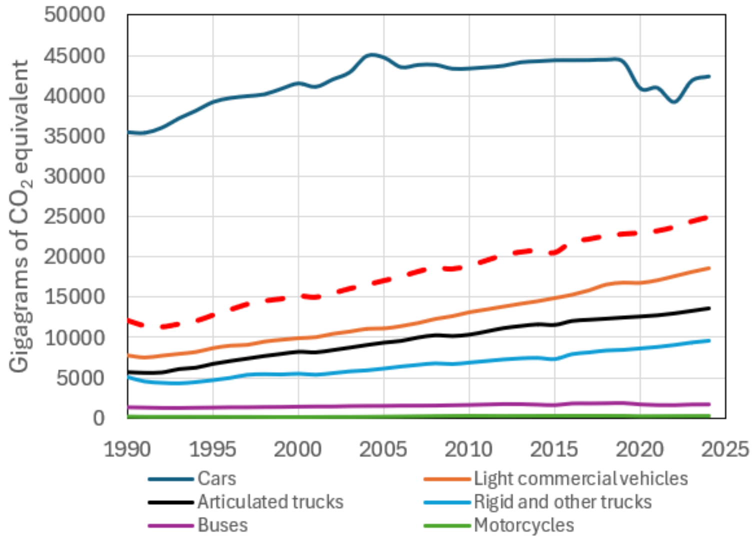

Figure 3. *Australia Road Transport Greenhouse Gas Emissions (Data Source: BITRE [11]).*

Although the electric trucks are attractive for commercial fleets due to their potential to reduce fuel consumption, lower total cost of ownership, and support the transition towards zero-emission freight, their adoption in Australia remains limited. This is largely due to unique regulatory constraints that are not aligned with the international standards. For instance, the maximum permissible truck width in Australia is 50 mm narrower than the United States, effectively restricting the import and sale of many American electric truck models [8].

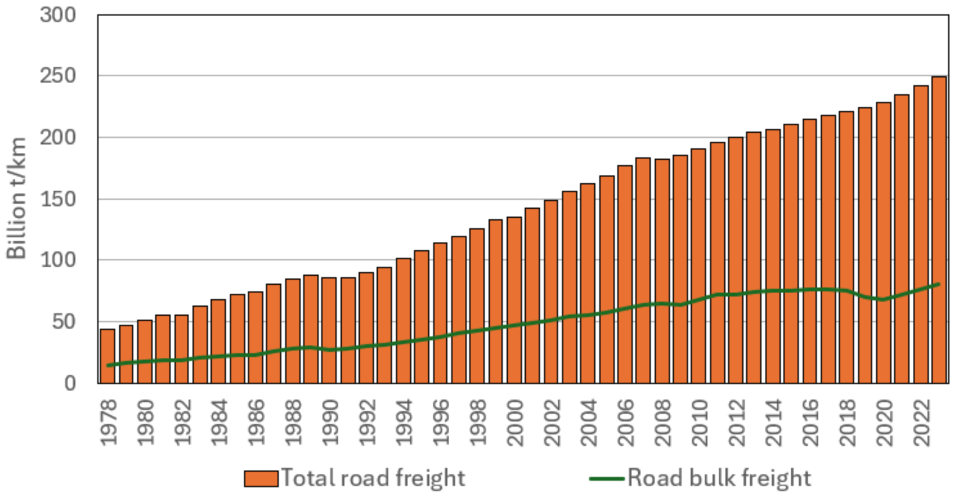

Figure 4. *Road Freight (Data Source: BITRE [11]).*

Over the years, road freight activity in Australia has exhibited steady growth, as illustrated in Figure 4. Driven by population growth, rising freight demand, and improvements in heavy vehicle productivity through increases in average vehicle size and load-carrying capacity, Australia's total freight task is projected to grow by 26% between 2020 and 2050. Within this total, road freight alone is expected to increase by approximately 77% over the same period [1, 13].

Capital cities and other urban areas account for approximately 34% of Australia's freight task, of which 44% is transported by light commercial vehicles and rigid trucks, while the remaining 56% is carried by articulated trucks [14]. This represents that roughly one-third of all road freight in Australia is concentrated within the major urban centres. Such a concentration offers immediate opportunities for electrification for the freight sector; however, progress is constrained by Australia's vehicle mass limits. In the short to medium term, and prior to the widespread establishment of charging infrastructure, electrification of short-haul freight operations in urban areas appears to be more practical and achievable pathway compared to remote or heavy-haul transport. This observation aligns with the findings of Liimatainen et al. [15], who reported similar trends in Switzerland and Finland. Notably, more than 80% of electric trucks currently available in the Australian market belong to the light- and medium-duty segments [8].

It is worth noting that Australia's truck fleet consists of approximately 50000 rigid trucks and 100,000 articulated trucks. Around one-third of the freight task undertaken by rigid trucks occurs in urban areas, whereas approximately two-thirds of the articulated truck freight task takes place in non-urban regions [16]. Given their smaller size, lower freight capacity, and higher utilisation within urban areas, rigid trucks present immediate and investable opportunities for electrification [17]. However, any reduction in the hauling capacity of electric trucks compared to their internal combustion engine counterparts may necessitate additional trips to transport an equivalent volume of freight. Such an outcome could, in turn, lead to increased traffic congestion and accelerated pavement deterioration.

3. Pavement Assets

Due to Australia's unique geography, climate conditions, and low population density- characterised by vast distances between major population and economic centres- the pavement types used across the country are designed using approaches and standards that differ significantly from those adopted in other parts of the world. Comparative pavement compositions between Australia and other countries illustrated in Figure 5. Establishing and maintaining an extensive network of sealed roads has therefore required the adoption of low-cost construction and maintenance techniques, most notably the use of sprayed seals applied over locally sourced marginal-quality road base or crushed rock [18].

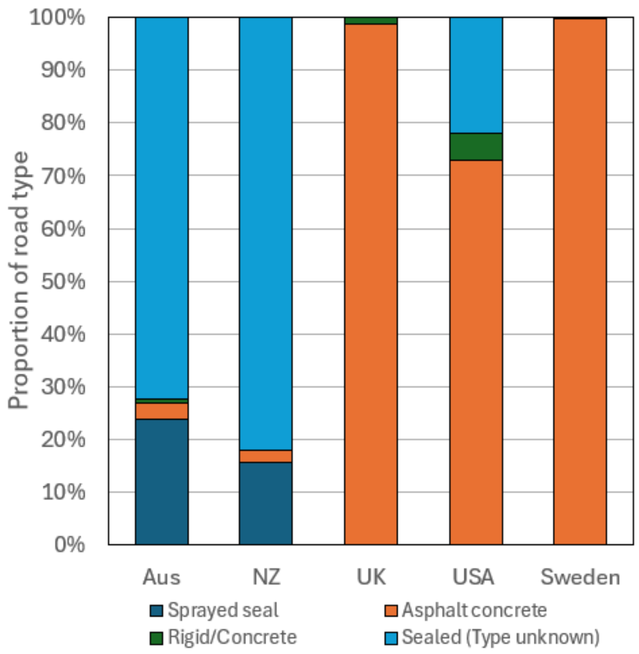

Figure 5. Pavement Composition (Data Source: Austroads [1]).

Pavement design practices in Australia are largely influenced by the country's predominantly dry climatic conditions, extensive arid inland regions and the associated low pavement moisture levels [19]. Consequently, the Australian freight network pavements primarily consist of sprayed seal or thin asphalt surfacing applied over unbound granular pavements. These lightweight pavement structures are well suited to the low-moisture environments characteristic of Australia's dry climate [20]. Typical cross-sections of thin asphalt or sprayed seal surfacing over unbound granular base pavements are illustrated in Figure 6. The majority of Australia's freight task operates on the state and national arterial road network, which has been specifically designed to support such economic activity. Figure 7 presents the distribution of state-managed arterial sealed pavements by pavement type and by state. The data clearly indicate that sprayed seal pavements dominate the sealed road network in Australia, accounting for approximately 85% of the total sealed road length nationwide.

In Australia, two primary types of pavement surfacing are employed: sealed and unsealed. A sealed road is the one in which the pavement surface is permanently sealed with a waterproof wearing course- such as sprayed seal, asphalt, or concrete- to improve ride quality, structural performance and durability under heavy traffic and higher-speed conditions [18]. This study focuses on sealed flexible pavements, specifically those comprising sprayed seal and thin asphalt surfacing applied over unbound granular base layers.

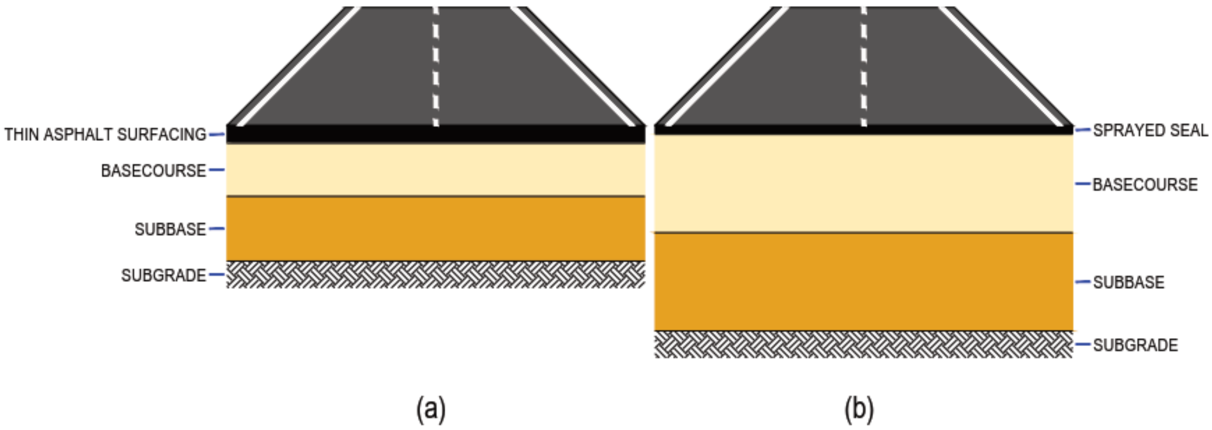

Figure 6*. Pavement types (a) Granular Pavements With Thin Asphalt Surfacing (b) Granular Pavements with Sprayed Seal Surfacing.*

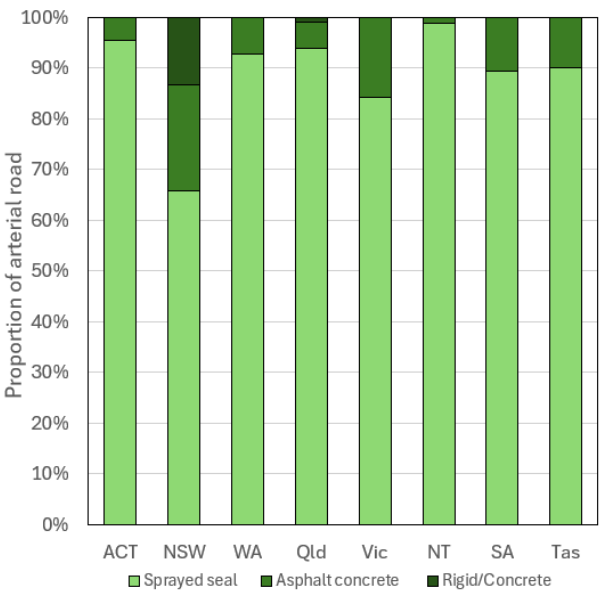

Figure 7*. Arterial Sealed Road Pavements by Pavement Type (Data Source: Austroads [1]).*

4. Steer Axle Loads

4.1. Truck Axle Load

In Australia, the mass, dimensions and loading of heavy vehicles are regulated under Heavy Vehicle National Law (HVNL). The general axle group mass limits for various vehicle configurations relating to allowable Gross Vehicle Mass (GVM) is summarised in Table 1. In practice, there are variations and exemptions to the prescribed maximum axle group masses depending on factors such as vehicle configuration, tyre width, the presence of road-friendly suspension systems, and compliance with the Performance Based Standards (PBS) and Vehicle Assessment Rules [21]. Discussion of Concessional Mass Limits (CML) and Higher Mass Limits (HML), which relate to increased permissible masses for specific heavy vehicle operations is beyond the scope of this review.

Table 1*. Maximum Mass Per Axle Group in Australia (tonnes).*

Characteristic	Axle group types	Gross mass limit (tonnes)
Single steer axle	Single axle with single tyres (SAST)	6.5

Characteristic	Axle group types	Gross mass limit (tonnes)
Single axle#	Single axle with dual tyres (SADT)	9.0
Tandem axle	Tandem axle with dual tyres (TADT)	16.5
Triaxle	Triaxle with dual tyres (TRDT)	20.0
Quad axle	Quad axle with dual tyres (QADT)	20.0
Gross mass limit (6 axle semi-trailers)		42.5

# denotes single axle with dual tyres (Data source: NHVR [22])

By comparison, the allowable mass limits for single axle groups in the United Kingdom and Sweden are more than 53% higher than those in Australia. Interestingly, the single steer axle mass limits in Australia and New Zealand are broadly comparable with each other but remain relatively lower than those in the United States, the United Kingdom and Sweden, as illustrated in Figure 8.

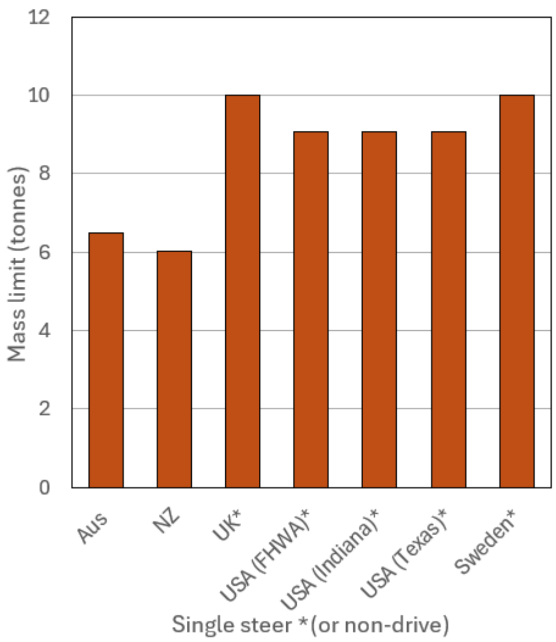

Figure 8. *Single Steer Axle Mass Limits (Data Source: Austroads [1]).*

The location of the battery system in an electric truck can significantly influence the vehicle's weight distribution and, consequently, the load carried by each axle. The additional mass of battery system can increase the overall vehicle weight, leading to higher loads on both the axles and the suspension system. Furthermore, the placement of the battery system can alter the vehicle's centre of gravity, thereby affecting its stability and handling characteristics. Increased axle loads in electric trucks can be further exacerbated during acceleration and braking, as the higher torque of electric powertrains compared to conventional internal combustion engines amplifies transient stresses on pavements and induces greater longitudinal stresses, as illustrated in Figure 9 [23]. Hernandez et al. [24] found that the location of the battery system, rather than the increased torque, is the dominant factor influencing vertical contact forces in electric trucks due to its effect on load distributions.

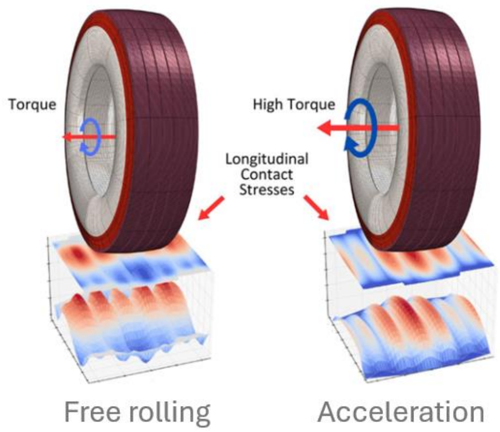

Figure 9. *Change in Longitudinal Contract Stress Distribution Due to High Torque (Adopted from FHWA [23]).*

4.2. Tyre Size, Tyre Pressure, Axle Configurations and Axle Loads

Pavement wear is influenced by several factors, including the number and types of axles, tyre size and pressure, the number of tyres, axle spacing and axle loads. A steer axle that carries a comparatively heavier load can impose more severe impacts on pavement deterioration than axle groups such as tandem or tridem configurations, where the heavier load is distributed across a greater number of tyres. This distribution results in equal or lower pavement stresses despite the higher total load.

Chen et al. [25] examined the impact of truck tyre pressures on pavements using a layered elastic model and a three-dimensional finite element computer program. Their findings indicated that both increased tyre pressures and heavier vehicle loads contribute to a reduction in the service life of pavements. In 1990, Hajek and Agarwal [26] investigated the influence of axle group spacing on pavement damage. Their results demonstrated that when the inter-axle spacing exceeds a certain threshold, which corresponds to an AASHTO load equivalency factor of 2.00, the two axles can be treated as independent. They concluded that axle spacing plays a significant role in the extent of pavement damage.

Gillespie and Karamihas [27] used computer simulations to study the influence of various truck factors on dynamic loads and subsequent pavement damage. Their study revealed that increasing axle load limit, using wide-base single tyres instead of dual tyres, increasing the recommended tyre pressure and, factors related to truck dynamic motion, all contribute negatively to pavement fatigue damage. Al-Qadi et al. [28] conducted a field study, supplemented by a finite element parametric analysis, to assess the effects of tyre configurations on pavement damage. Their findings reveal that wide-base tyres cause equal to or greater pavement damage compared to conventional dual tyres. In the subsequent study, Al-Qadi and Wang [29] used three-dimensional (3-D) finite element models to predict pavement responses to loading applied by different tyre configurations on secondary road pavements. Their results showed that the impact of new generation wide-base tyres varies considerably in comparison to conventional dual tyre assembly. Under identical loading conditions, wide-base tyres caused 1.9-2.5 times more fatigue damage, 1.31-2.35 times more subgrade rutting and, 1.35-1.77 times more fatigue damage compared to the conventional dual tyre assembly.

Austroads [30] used an accelerated loading facility to study the relative pavement wear of unbound granular pavements with thin bituminous surfacing, applying a 40 kN half axle load using various tyre types. The study found that the rate of increase in surface deformation for the wide single tyres and steer tyres was higher compared to the reference dual tyres. Interestingly, a study by Varin and Saarenketo [31] for ROADEX countries showed that rutting increased by 8 to 18 times more with super single tyres than with dual tyres. In 2016, Austroads [32] examined the optimum steer mass limits for road trains, concluding that ideal steer axle mass limit is 7.0 tonnes, with a wider tyre size greater than 375 mm. Arshad et al. [33] conducted a full-scale experiment and used the KENPAVE linear elastic program to analyse pavement responses to varying tyre pressure of heavy vehicles. Their findings indicated that high tyre pressures result in smaller contact areas, which adversely impact on the flexible pavements.

In the United States, mass limits have remained mostly unchanged for the last 50 years, primarily constrained by the load-bearing capacity of the bridges. In the United Kingdom, the GVW was increased by 2 tonnes to support the adoption of ZEHVs, provided that the total vehicle mass does not exceed 44 tonnes. In contrast, Australia enforces lower axle mass limits compared to international standards, although these limits are fully utilised within the broader constraints of vehicle mass limits. In 2018, California adopted a 2000 lb (907 kg) increase in GVW for near-zero and zero-emission vehicles, while maintaining the existing weight limits for individual axles, in order to encourage ZEHV adoption [34]. A similar legislative change was introduced in Pennsylvania in 2021 [35]. When considering the same maximum axle load and excluding longitudinal contact stresses, the additional weight of 907 kg from electric vehicle batteries results in only a minimal increase in pavement damage. Generally, higher axle loads lead to greater pavement strain, which accelerates damage and contributes to overall pavement deterioration [34].

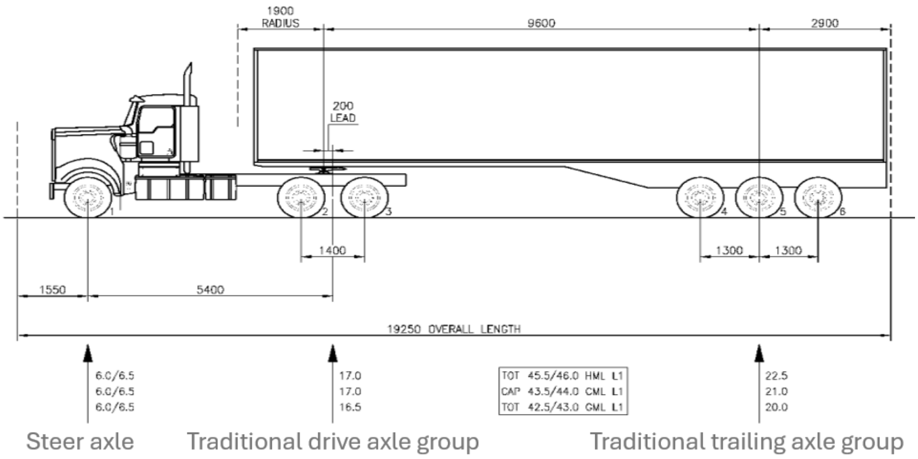

Figure 10. *Typical Semi-trailer of 19.25m Length (Adopted from Williamson and Takeuchi [37]).*

Varin and Saarenketo [31] found that increasing the weight of Swedish truck to 74 tonnes results in a 1.2-fold increase in the pavement wear compared to traditional 60-tonne trucks. In 2018, Sweden raised the maximum GVM from 64 tonnes to 74 tonnes. In a subsequent study, Varin and Saarenketo [36] evaluated the impact of heavier loading, tyre size and pressure, axle configurations and the number of axles on pavement deterioration. The study revealed several key findings: dual tyres are less damaging to pavements than super single tyres; high tyre pressures exacerbate the detrimental impact on pavements, with pavement lifespan at 1000 kPa tyre pressure reduced to half that of 800 kPa pressure; increasing the number of axles does not mitigate pavement wear as closer axle spacing creates a wave of pressure that prevents the pavement from elastically recovering before being loaded again- this effect is particularly significant for soft subgrade conditions, such as freeze- thaw cycles or flooding.

Furthermore, Varin and Saarenketo [3] studied inter-axle distances and concluded that spacing greater than 1.6 m spacing has negligible effect on pavement wear, with a minimum inter-axle distance is 1.3 m being significant. They also recommended that the minimum distance between combined axle groups should be 3 m, noting that distances beyond 3 m have no major effect on elastic recovery times or pavement response. Interestingly, the axle and inter-axle spacing used in commercial truck in Australia, as shown in Figure 10, aligns with these findings. The study also observed that the estimated pavement lifetime for a 10-tonne axle weight is approximately 25-35% shorter than that for an 8-tonne axle weight. However, this study may not be entirely applicable to Australian road conditions, particularly because a large portion of Australia's road network consists of unbound granular pavements with thin bituminous surfacing, which were not considered in this research.

Saliko and Erlingsson [38] investigated the damage on thin flexible pavements to longer, heavier vehicles with a 74-tonne GMV, as adopted by Swedish Road Authority. Using instrumented road sections and numerical calculations, their findings indicated that, as long as the number of axles is increased to compensate for the higher vehicle loading, and dual tyres are used, the impact on the too thin pavement structures is not more severe than that caused by lighter vehicles with fewer axles but higher average axle loads and tyre pressures.

4.3. Truck Size

The National Transport Commission has indicated that the maximum length limit for heavy vehicles is a significant constraint on fright vehicle productivity [39]. If the length limit for freight vehicles is increased while maintaining volume constraints, these vehicles are likely to operate at higher gross masses. This, in turn, can lead to a substantial increase in pavement wear, as illustrated in Figure 11.

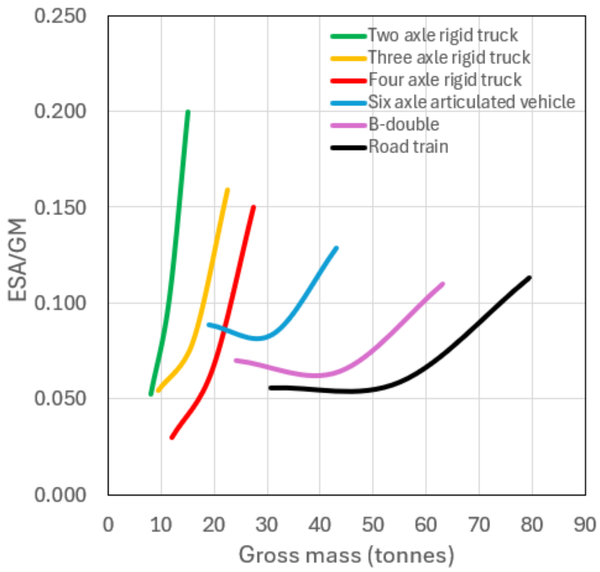

Figure 11. *Variation in Maximum ESA/GM Wear with Gross Mass of Various Heavy Vehicle Types.*

Australia employs PBS approach to regulate vehicle size and weight, with a focus on safety and environmental objectives. The PBS framework is applied to custom-designed trailers intended for specific load movements, often associated with route restrictions, and has been in operation since the mid-2000s. Australia is home to some of the largest trucks in the world, as shown in Table 2 [40, 41]. Notably, road train triaxle dollies are used exclusively on remote rural national highways.

The maximum legal overall length of commercial vehicles in Australia is measured from bumper to bumper. In terms of width, Australian trucks are limited to 2.5 m, whereas trucks in Europe are permitted to be 2.55 m wide (with refrigerated vehicles allowed up to 2.6 m). Trucks in the United States have similar width of 2.6 m [4, 42]. This discrepancy indicates that Australia’s truck width standard does not align with those of major global economies. Any future design modifications to adapt a 2.5 m width would likely face challenges and may not be economically viable, particularly considering the relatively small market for battery electric trucks in Australia [9].

Table 2. *Truck Sizes.*

Country	Maximum truck size		
	Vehicle length (m)	**Vehicle width (m)**	**Vehicle height (m)**
United States	14.63	2.60	4.15-4.45
Mexico	31.00	2.60	4.25
Canada	25.00	2.60	4.15
European Union	18.75	2.55	4.00
Australia	30.00 – 53.50#	2.50	4.30 – 4.60

Data source: FHWA [40, 41] and ATA [43].
# denotes road train triaxle dolly, used only in remote rural national highways

4.4. Truck Weight Limits

In Australia, the general mass limit for a vehicle is determined by the sum of the approved axle group masses. In contrast, other jurisdictions often set the overall vehicle mass limit independently of the axle group masses, with the total vehicle mass typically being lower than the sum of the allowable axle group masses. This approach offers greater flexibility in vehicle loading, allowing for adjustments in axle group masses without affecting the total vehicle mass or payload. For example, in Sweden, the permitted maximum gross weight is determined by the spacing between the first and last axle, based on the vehicle combination and the load capacity of the road classification [1].

Heavy vehicles have a minimum two axles: the steer axle and drive axles. The steer axle is positioned at the front of the vehicle, enabling the driver to control the direction, while the drive axles transmit the power generated by the engine to the wheels. In the case of articulated heavy vehicles, the trailer axle is located on the trailer to support the vehicle mass, as illustrated in Figure 10. Generally, the steer axle exerts higher loading on the pavement structure compared to the combined load of other group of axles elsewhere on the vehicle [1].

For illustration, this study compares the commonly used 19 m semi-trailer freight truck to determine the gross mass limit used by various jurisdictions. In Australia, the gross mass limit for 19m semi-trailer is 42.5 tonnes. This limit is determined based on the sum of a 6-tonne single steer axle mass limit, a 16.5-tonne tandem axle group mass limit, and a 20-tonne triaxle group mass limit [44]. Additionally, tandem and tridem axles are permitted an extra 0.5 tonnes and 2.5 tonnes respectively, if equipped with road-friendly suspensions, though tridem axles are subject to route restrictions [40]. It is important to note that if vehicles exceed the legal mass limits, they become less stable and take longer to stop in an emergency, posing significant safety risks [1].

In the United States, the gross mass limit for heavy vehicles is set at 36.3 tonnes, provided that no single axle exceeds 9.07 tonnes. This approach, in place since 1974, offers flexibility in how axle groups can be loaded, but there are no plans to increase the mass limit, primary due to concerns over the impact of heavy vehicle mass impacts on bridges. The United States' approach to mandating the gross mass limit underscores that any increases in mass limits are constrained by the load-bearing capacity and condition of bridge infrastructure.

In the United Kingdom, the gross mass limit is set at 44 tonnes, depending on the number of axles and whether the vehicle is equipped with road-friendly suspension [45]. In Sweden, the gross mass limit is determined by the distance between the first and last axle groups. For a vehicle with a 16.1 m spacing between the first and last axles, a total vehicle mass of 64 tonnes is permitted on BK4 roads, and 56 tonnes on BK1 roads [46]. Finland and Sweden allow higher gross mass limits compared to many other jurisdictions. In 2013, Finland increased the maximum permissible vehicle mass to 76 tonnes, followed by Sweden in 2018, whereas several other European countries continue to enforce 44-tonne limit [47].

In summary, the gross mass limits for heavy vehicles in the United Kingdom and the United States are comparable and generally more consistent with those applied in Australia. However, as the regulation in these countries is based on the total mass across all axles on the semi-trailer, rather than on individual axle groups, the steer axle load can potentially be significantly higher than that permitted in Australia.

5. Pavement Wear

All relevant available published literature has been collated, screened and reviewed as part of the literature review process to ascertain the knowledge gap.

Currently, the National Heavy Vehicle Regulator in Australia has prescriptive regulations for heavy vehicle mass, dimensions and configuration. At present, there is no nationally standardised methodology for evaluating unacceptable pavement wear [48]. Historically, pavement wear potential is measured using the 4th power of axle group load, more commonly referred to as the Equivalent Standard Axle. More recently, pavement wear ratio is used in the UK to quantify pavement wear. The third approach is using weigh-in-motion data to mechanistic quantify the damages impacted on pavements by heavy electric vehicles. These methods are used to assess the effect of a 1-tonne increase in steer axle mass on pavement wear and as detailed in the following sections.

5.1. Pavement Wear Ratio

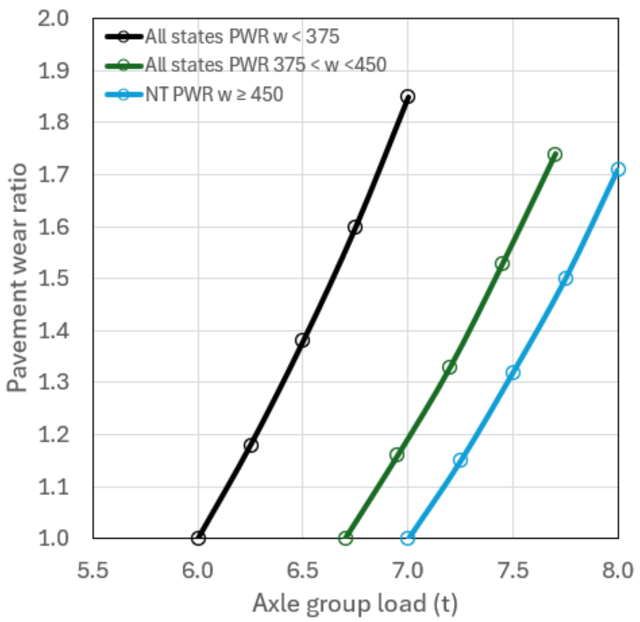

Figure 12. *Pavement Wear Ratio (PWR) for Various Axle Group Load.*

Majority of sealed roads in Australia comprise sealed unbound granular pavements. The effect of steer axle mass on these pavements is assessed using the Pavement Wear Ratio (PWR), which is determined for an axle under the varying axle loads. The PWR is defined as the ratio of the Equivalent Standard Axle (ESA) for wide single tyres to the ESA for dual tyres at a specified axle load [32]. Figure 12 summarises the PWR determined for various axle group loads and tyre widths across all Australian states, including the Northern Territory (NT). These results suggest that an increase of 1.0 tonne in street axle mass leads to a 71-85% increase in pavement wear ratio. This relationship is illustrated in Figure 12, where plotted lines show a steep gradient even for minor increases in axle load. It should be noted that these percentage increases reflect the relative damage attributed to the steer axle alone. In practice, the overall increase in pavement wear for a complete commercial vehicle would be lower, as the additional load is not distributed across the remaining other axles. Furthermore, for a given axle group load, pavements subjected to narrower tyres exhibit a substantially lower PWR compared to those fitted with wider tyres, as shown in Figure 12.

5.2. Road Wear Potential

Rhodes [49] and other researchers, including Austroads [44], have applied the fourth power law of axle group load to quantify the cumulative pavement damage in terms of ESA repetitions. The ESA is a non-dimensional measure of the relative wear associated with different axle loads, axle configurations and tyre types. The total ESA for a vehicle is obtained by summing the ESA values corresponding to each axle group [50]. A load damage exponent of four is commonly adopted for granular pavements with thin bituminous surfacing, which constitute most of the Australian road network. For instant, a 10% increase in axle load is estimated to increase pavement wear by approximately 46%, while doubling the axle load results in a sixteen-fold increase in pavement wear [1]. It is important to note that the ESA remains the most widely used index of pavement wear in road pricing and economic analyses both within Australia and internationally [48].

The ESA for each axle group with single and dual tyres at the current prescriptive mass limits are summarised in Table 3 [48]. Interestingly, the pavement wear varies markedly between axle group types at these prescriptive axle load limits. It shows that the pavement wear (ESA/gross mass) of single axle with dual wheels is more than twice the value for triaxles. In addition, single axle with single wheel is the highest pavement wear when compared with all other axles with single and dual wheels. This infers that any change to axle group type load limits especially single and tandem axle with single tyre will have the potential to cause higher impact on pavement wear. Furthermore, the performance measure to reduce pavement wear risk can be mitigated by removal of the mass constraints to drive and trailing axle groups.

Table 3. *ESA of Pavement Wear at Prescriptive General Mass Limits.*

Axle group type	Axle group mass (tonnes)	ESA	ESA/axle group mass (tonnes)
Single axle with single tyres (SAST)	6.0	2.10	0.25

Axle group type	Axle group mass (tonnes)	ESA	ESA/axle group mass (tonnes)
Single axle with dual tyres (SADT)	9.0	1.48	0.16
Tandem axle with single tyres (TAST)	11.0	2.06	0.19
Tandem axle with dual tyres (TADT)	16.5	2.06	0.13
Triaxle with dual tyres (TRDT)	20.0	1.38	0.07
Triaxle with wide singe tyres (TRST)	20.0	3.25	0.16
Quad-axle with dual tyres (QADT)	24.0	1.20	0.05

Data source: Austroads [48].

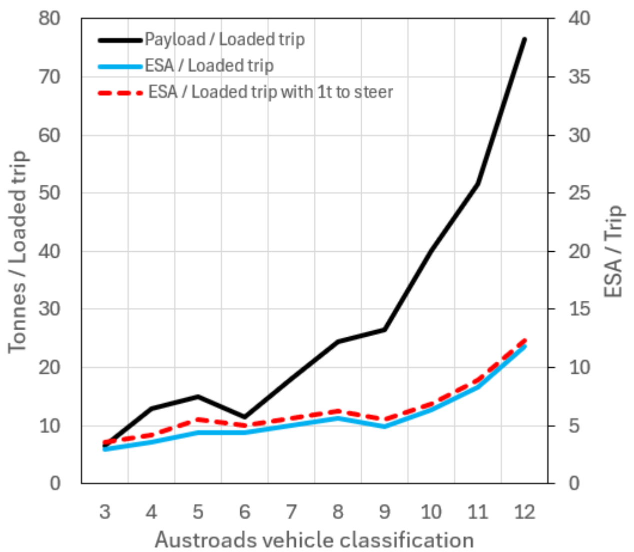

Figure 13. *Relationship Between Payload and ESA for Austroads Heavy Vehicle Classes (Adapted from DTMR [52]).*

A reduction in truck payload results in a corresponding decrease in the ESA value. The relationship between full payloads- including an addition 1-tonne on steer axle- and the ESA for each Austroads heavy vehicle class is graphically demonstrated in Figure 13. The figure shows that a 1-tonne increase in steer axle load produces only a marginal increase in ESA per loaded trip compared with the baseline condition. It also reveals a sharp increase in payload per loaded trip for vehicle classes of seven and above. This finding supports the rationale that larger, long-haul vehicles are more efficient for transporting high payload volumes, as they distribute loads more effectively across multiple axles. Similar conclusions were drawn by Chatti et al. [51], who, based on laboratory testing and field data, observed that vehicles equipped with tridem or multiple axle groups caused less pavement wear per tonne of freight carried than those with single or tandem axles.

This approach is extended to assess the entire vehicle across different vehicle classes by assuming a 1-tonne load increase in the SAST, while keeping other axle loads constant for comparison purposes. The effect of this 1-tonne increases in SAST on the ESA for all conventional vehicles, which ranges from 11 to 43%, is summarised in Table 4. The results show that rigid trucks are significantly more affected than road trains. This can be attributed to the fact that road trains have a higher rear axle load compared to rigid trucks, and the impact of the increase in SAST is mitigated by the absence of additional load on the other axles. The nomenclature terminology in Table 4 uses alphabetic and numeric prefixes to denote the type of vehicle and the number of axles in each axle group respectively. For clarity, "R" and "A" mean rigid and articulated vehicles. For instance, "A123" means articulated vehicle with single axle, tandem axle and triaxle.

Table 4. *Effect of a 1-Tonne Increase in SAST on ESA.*

Vehicle description	Vehicle class	Nomenclature used	No increase in SAST (ESA)	Increase SAST by 1 tonne (ESA)	Percentage increase (%)
Two axle truck	3	R11	3.00	4.30	43.2
Three axle truck	4	R12	3.59	4.88	36.2
Four axle truck	5	R112	5.07	6.37	25.6
Three axle articulated vehicle	6	A111	4.49	5.79	28.9
Four axle articulated vehicle	7	A112	5.07	6.37	25.6

Vehicle description	Vehicle class	Nomenclature used	No increase in SAST (ESA)	Increase SAST by 1 tonne (ESA)	Percentage increase (%)
Five axle articulated vehicle	8	A122	5.65	6.95	22.9
Six axle articulated vehicle	9	A123	4.94	6.24	26.3
B Double	10	A1233	6.29	7.59	20.6
Double road train	11	A12323	8.36	9.65	15.5
Triple road train	12	A1232323	11.77	13.07	11.0

Data source: Austroads [44].

Building on this established relationship, Low et al. [53] introduced the concept of Road Wear Potential (RWP) of individual vehicle, which is expressed in Equation (1).

$$RWP = (No.of\ axles) \times \left(\frac{Vehicle\ weight}{Number\ of\ axles \times 80}\right)^4 \qquad (1)$$

The effect of a 1-tonne increases in SAST on the RWP for all conventional vehicles, which ranges from 4% to 30%, is illustrated in Figure 14. The results show that rigid trucks are more significantly impacted compared to road trains. This can be attributed to the higher rear axle load of road trains, which reduces the impact, as there is no increase in load on the other axles.

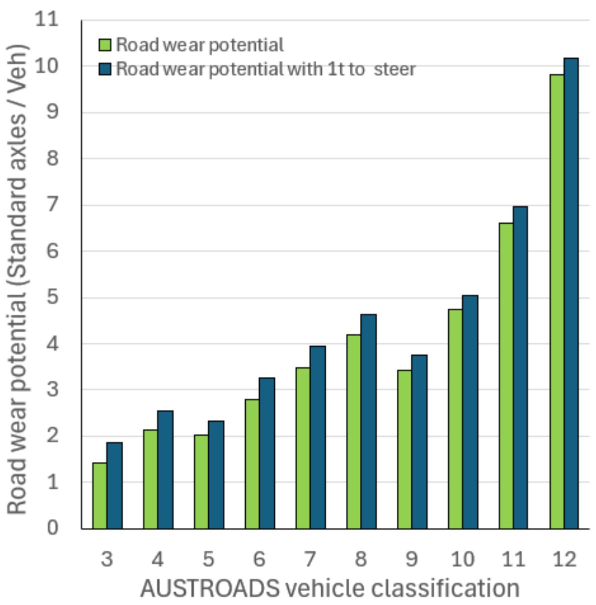

Figure 14. *Effect of a 1-Tonne Increase in SAST on RWP.*

5.3. Pavement Wear Using Weigh-in-motion (WIM) Data

The use of publicly available weigh-in-motion (WIM) station data offers significant advantages over relying on individual vehicle axle or total vehicle axle load to determine pavement wear. This approach enables the pavement designers to assess wear across a full spectrum of axle weights and vehicle types within the traffic distribution, rather than limiting the analysis to a single axle load. As a result, frequency distributions for each axle weight group and vehicle class are considered in the assessment, providing a more comprehensive understanding of the pavement's response to traffic loads. State-of-art WIM equipment can collect critical data such as vehicle and axle weights, axle spacing, speed and vehicle class, allowing for detailed analysis of the factors contributing to pavement deterioration. However, it is important to knowledge that WIM data has limitations. These limitations arise unless the data is continuously compiled and updated, with enhanced geographical coverage, to improve the overall quality of the data. Furthermore, the high cost of installing WIM stations remains a significant concern [40]. In addition, current WIM data collection alone cannot provide reliable vehicle class travel estimates, and there is a poor correlation between static and dynamic axle load measurements [54]. These challenges highlight the need for ongoing improvements in data collection methods and equipment to ensure more accurate and actionable insights for pavement design.

Australia has a relatively low density and a high length per capita road network, compared with other countries, resulting in extensive rural road networks predominantly comprising of sprayed-sealed or unsealed granular pavements [1]. Local road networks are typically consisting of thin asphalt surfacing over unbound granular base and subbase layers. Hence, this study focuses on sealed flexible pavements, specifically sprayed seals on national and rural highways and thin asphalt surfacing over unbound granular pavements on local roads. Within the local road category, five street types representing local access and collector roads, commonly used by commercial heavy vehicles are examined. Pavement profiles can vary considerably due to differences in design traffic loading, vehicle masses, ground conditions, and local preferences. For this study- assessing and comparing pavement responses to a 1-tonne increase in steer axle load- the commonly used pavement profiles for local roads and rural national highways, as detailed in Table 5, are adopted.

The pavement profile terminology presented in Table 5 uses alphabetic and numeric prefixes to denote pavement layer type and thickness, with variations indicated where subgrade conditions differ. For clarity, AC, BC, SB and SS represent asphalt, basecourse, subbase and sprayed seal, respectively. For example, 50AV/130BC/variesBC refers to 50 mm asphalt layer, 130 mm basecourse layer and a subbase layer of variable thickness depending on subgrade conditions.

Table 5. Effect of Steer Axle Mass on Local Roads and Rural National Highways.

Street type	Pavement profile	Design traffic N_{ESA} (ESA)	Design traffic N_{DT} (HVAG)	Average cumulative HVAG with 1t increase to steer axle	Average percentage reduction (%)
Local access with no buses	40AV/100BC/variesSB	4.0×10^4	1.50×10^5	7.68×10^4	48.7
Local access with buses	50AV/110BC/variesSB	8.0×10^4	1.81×10^5	1.13×10^5	37.2
Local access in industrial area	50AV/120BC/variesSB	1.5×10^5	2.96×10^5	1.92×10^5	35.0
Collector with no buses	50AV/130BC/variesSB	4.0×10^5	6.82×10^5	3.93×10^5	42.2
Collector with buses	80AV/150BC/variesSB	8.0×10^5	1.22×10^6	8.40×10^5	31.3
Rural national highways	SS/250BC/variesSB	2.0×10^7	2.04×10^7	1.61×10^7	20.9

Source: Design traffic data from Austroads [44] and VicRoads [56].

A large number of WIM station datasets available across Australia are documented in Austroads [44]. For this study, traffic load distribution (TLD) data for local roads and rural national highways roads are sourced from Austroads [44] and VicRoads [55], respectively. The presumptive TLD data for local roads provided by Austroads are based on the study by Matthews and Mulholland [56] on residential road pavement design. The WIM data for each road type cover the full spectrum of TLD, including the frequency distribution for each axle type and their respective proportions within the overall traffic. The TLD was subsequently adjusted to incorporate a 1-tonne increase in SAST, as shown in Figure 15. It is evident that lower axle group loads dominate the TLD for local roads compared with that of rural national highways. Based on the TLD data, the proportion of SAST ranges from approximately 44% to 48% for local roads, compared with about 29% for rural national highways.

The ESA/HVAG conversion factor for each TLD is estimated following the Austroads procedure [44]. This conversion factor is then used to convert the design traffic ESA into cumulative Heavy Vehicle Axle Group (HVAG) for input into the pavement design software CIRCLY. In addition, the modified TLD is imported into CIRCLY's linear elastic program to determine pavement design life. The analysis considered varying subgrade CBR values (3%, 5% and 10%) to account for the range of soil conditions encountered in the field. It is important to note that thin asphalt or sprayed seal layers over unbound granular pavements are assumed to provide no structural contribution to the required granular material thickness [44].

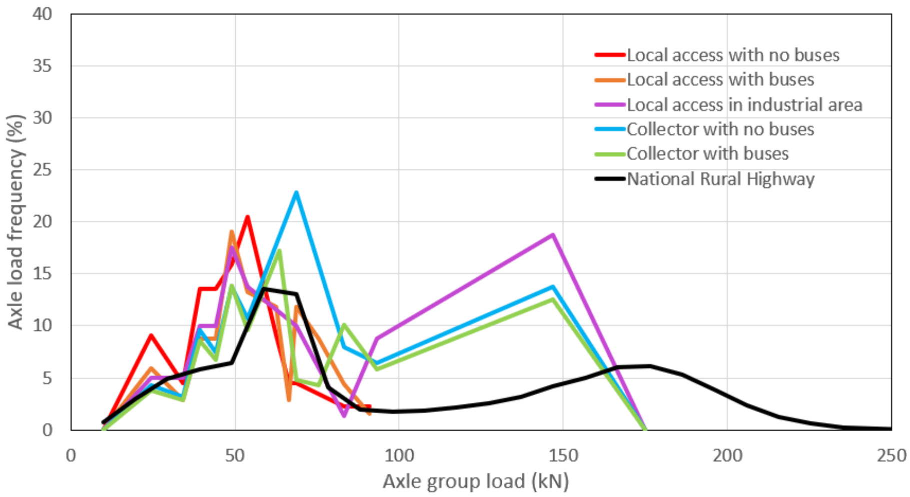

Figure 15. Modified TLD for Local and Rural National Highways.

Table 5 summaries the effect of a 1-tonne increase in steer axle mass on local and rural national highways. The results indicate that local roads are generally more severely affected, with pavement life reductions of 31.3-48.7%, compared with the 20.9% reduction for rural national highways. This difference is attributed to design traffic for local roads, which consists of a higher percentage of lower vehicle classes with fewer axles, whereas road trains on rural national highways, mitigating the impact of increased in the steer axle load. These findings are consistent with observations by the United Sates Department of Transportation, which reported that a 907 kg (2,000 lbs.) increase in axle weight can result in approximately 50% more pavement damage, as noted by Haddock [57]. The impact of a 1-tonne increase in steer axle mass on pavement life is illustrated in Figure 16. Interestingly, the results indicate that, assuming all other conditions are constant for a given local road type, the percentage reduction in pavement life is approximately the same across different subgrade conditions.

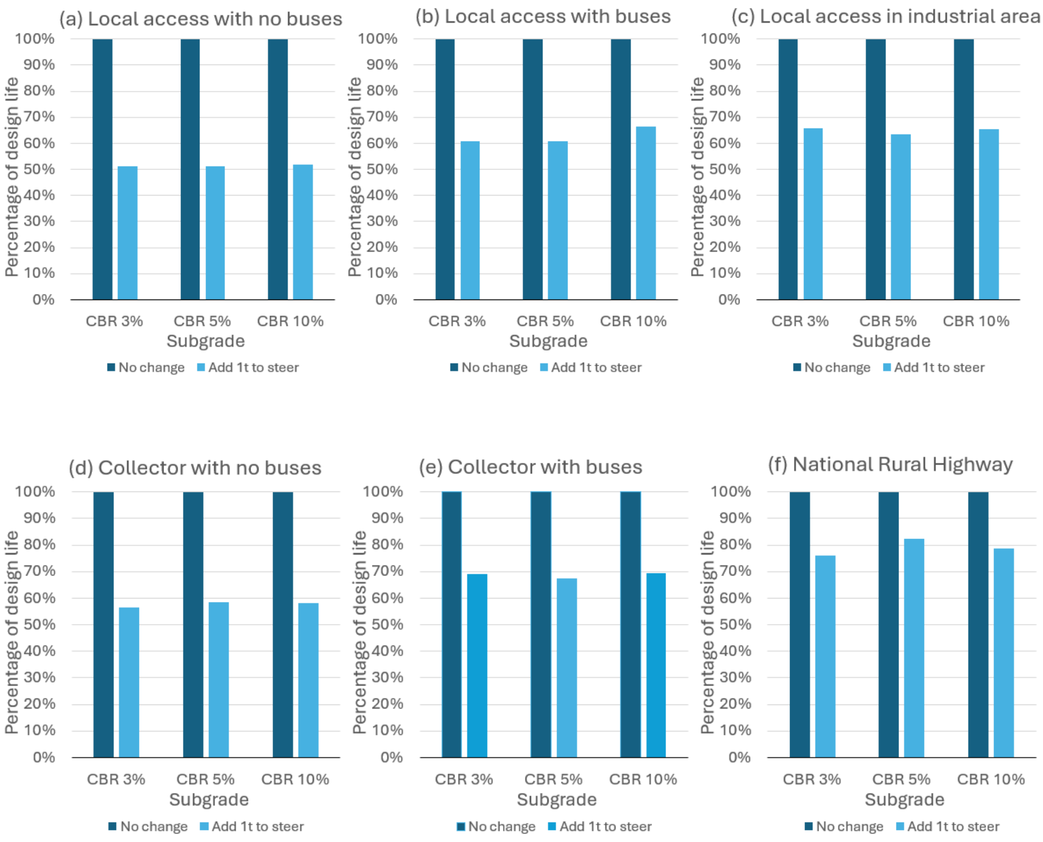

Figure 16. Effect of a 1-Tonne Increase in Steer Axle Mass on Local Roads and Rural National Highways.

In summary, a 1-tonne increase in steer axle load leads to higher pavement wear and a significant reduction in pavement life, particularly on local roads. This finding is consistent with FHWA [23] recommendations, which advise against placing heavy-duty electric vehicle battery system on the steer axle and suggest an evenly distributed load scenario to minimise pavement wear.

5.4. Summary of Pavement Wear Methods

The pavement wear methods, capabilities, advantages, and limitations are summarised in Table 6.

Table 6. Summary of Pavement Wear Methods.

Method	Analysis	Comments
PWR	Empirical	Use in the UK. Limited to ratio of single tyre to dual tyre axle assessment. Cannot assess pavement damage for the whole vehicle and pavement service life.

Method	Analysis	Comments
RWP	Empirical	Widely used to assess pavement damage imparted by axle group mass and all conventional road vehicle class categorized in Austroads. Cannot be used to do mechanistic quantification of pavement damage and prediction of pavement service life or loss of pavement life
WIM	Mechanistic	More accurate method with ability to cover full spectrum of traffic load distribution. Can be used to do mechanistic quantification of pavement damage and prediction of pavement service life reduction. Rely on availability of site-specific WIM/TLD data sets. Alternatively, use presumptive WIM/TLD data set from Austroads and VicRoads if site specific WIM/TLD data set is not available.

6. Conclusion

The decarbonisation of heavy vehicles through the introduction of Zero-Emission Heavy Vehicles (ZEHV) technologies, such as electric trucks, represents a paradigm shift in freight transport with significant implications for pavement deterioration. This desktop study reviews the interactions between electric trucks and pavements to assess the impact of heavier steer axle loads. The literature indicates that there is currently no nationally agreed-upon process for assessing unacceptable pavement wear.

Three approaches were used to assess the effect of increasing steer axle mass by 1 tonne. The Pavement Wear Ratio (PWR) approach indicates that a 1-tonne increase in steer axle mass contributes to approximately 71-85% of the pavement wear potential, reflecting the damage attributed to the steer axle alone. This significant increase in RWP could potentially be mitigated in the future through lighter battery technologies, which are not yet. Road Wear Potential method shows that the effect of a 1-tonne increases in the Single Axle Single Tyre (SAST) load results in 4-30% RWP for all heavy vehicles with rigid trucks being more significantly affected than road trains due to the fourth-power load effect, while the higher rear axle load of road trains mitigates the impact. This is largely due to fourth power effect with road train has more rear axle load when compared with rigid truck and the impact is attenuated with no increased in load for the remaining other axles. The use of weigh-in-motion (WIM) data provides a superior method for estimating pavement wear compared with relying on individual vehicle axle or total axle loads, as it captures the full spectrum of axle weights and frequencies in traffic. Analyses using WIM data indicate that a 1-tonne increase in steer axle mass results in 31.3-48.7% reduction in pavement life on local roads, compared with 20.9% reduction on rural national highways. This effect is primarily due to the higher load concentrated over a smaller contact area at the steer axle, which accelerates pavement deterioration.

Overall, the findings suggest that increases in steer axle mass will lead to higher maintenance costs to address accelerated road damage or require acceptance of a reduced level of service, with associated implications for road network efficiency and safety.

7. Limitations

This study is applicable only for a set of specific conditions. *First*, the pavement wear assessment using the WIM approach applies to thin asphalt or sprayed-seal surfacing over unbound granular bases for assumed subgrade conditions; the effects on other pavement types, such as full-depth asphalt, modified or stabilised materials, or concrete, require further investigation. *Second*, dynamic axle group loading is not considered. *Third*, the analysis is limited to the single axle with single tyre (SAST) configurations. *Fourth*, single-tyred and dual-tyred axle loads are assumed to act over uniformly loaded areas with constant tyre pressures of 800 kPa and 750 kPa, respectively. *Fifth*, the impact of higher torque in electric trucks on near-surface pavement strains is not considered. *Sixth*, variations in vehicle typology, battery location, and mass distribution between steer and drive axles are excluded. *Seventh*, safety implications of increasing allowable steer axle weight are not evaluated. *Eighth*, practical engineering challenges associated with a heavier steer axle loads are not investigated. *Nineth*, the study is limited to eighteen pavement structures using modify TLDs; other combinations of TLDs, load configurations, and tyre pressures may yield different outcomes. *Tenth*, the pavement distress is evaluated based on the subgrade shape loss through rutting accumulation, while plastic deformation of asphalt and granular base layers is not considered. *Eleventh*, cost/maintenance impacts are beyond the scope of this study. *Finally*, the effects of electric trucks on bridges are not addressed.

Abbreviations

GHG	Greenhouse Gas
ZEHV	Zero-Emission Heavy Vehicles
EV	Electric Vehicles
IEA	International Energy Agency
CO_2	Carbon Dioxide
ACT	Australian Capital Territory
NSW	New South Wales
WA	Western Australia
Qld	Queensland

Vic	Victoria
NT	Northern Territory
SA	South Australia
Tas	Tasmania
BITRE	Bureau of Infrastructure and Transport Research Economics
GVM	Gross Vehicle Mass
PBS	Performance Based Standards
CML	Concessional Mass Limits
HML	Higher Mass Limits
SAST	Single Axle with Single Tyres
SADT	Single Axle with Dual Tyres
TAST	Tandem Axle with Single Tyres
TADT	Tandem Axle with Dual Tyres
TRST	Triaxle with Wide Singe Tyres
TRDT	Triaxle with Dual Tyres
QADT	Quad Axle with Dual Tyres
NHVR	National Heavy Vehicle Regulator
FHWA	Federal Highway Administration
AASHTO	American Association of State Highway and Transportation Officials
3-D	Three-dimensional
ATA	Australian Trucking Association
HV	Heavy Vehicles
PWR	Pavement Wear Ratio
ESA	Equivalent Standard Axle
DTMR	Department of Transport and Main Road
R and A	Vehicle Nomenclature R Is Rigid and Articulated Vehicles
RWP	Road Wear Potential
WIM	Weigh-in-Motion
AC	Asphalt
BC	Basecourse
SB	Subbase
SS	Sprayed Seal
HVAG	Heavy Vehicle Axle Group
CBR	California Bearing Ratio
N_{ESA}	Design Traffic in ESA
N_{DT}	Design Traffic in HVAG
NW&RA	National Waste & Recycling Association
NHVR	National Heavy Vehicle Regulator
EVC	Electric Vehicle Council
ABS	Australian Bureau of Statistics
EPA	Environmental Protection Agency
NTC	National Transport Commission

Author Contributions

Boon Tiong Chua: Conceptualization, Data curation, Investigation, Resources, Validation, Formal analysis, Methodology, Software, Writing – original draft, Writing – review & editing.

Kali Prasad Nepal: Validation, Writing – review & editing.

Conflicts of Interest

The authors declare no conflicts of interest.

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