Australasian Transport Research Forum 2021 Proceedings
8-10 December, Brisbane, Australia
Publication website: http://www.atrf.info

Do Trackless Trams need stronger roads? – the "weight" of evidence

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Abstract

Trackless Trams are a new generation of advanced bus technologies with significant potential for application as a cost-effective alternative to Light Rail Transit. They have significantly lower estimated construction and infrastructure costs (-67% to -84%) compared to Light Rail since they can use existing roads and don't need expensive rail tracks. However, they are very heavy vehicles that have the potential to cause pavement damage, suggesting a need for road strengthening works. The manufacturer claims they can be used on any road without the need for road pavement treatments and, because of this, can be implemented in only a few days.

This paper explores the road pavement impacts of new Trackless Tram bus technologies. It finds Trackless Trams weigh between 32 and 85 Tonnes and would be amongst the heaviest vehicles used on roads. An independent inspection of existing Trackless Tram sites is reported in the paper. This discovered evidence of road pavement damage, suggesting that claims for a 'weekend' system construction period using existing road pavements are very optimistic. Modelling of road pavement performance suggests Trackless Trams are likely to require significant road pavement strengthening under almost all scenarios modelled. The traffic load bearing impact of Trackless Trams is between 14 and 221 times higher than common loads on even high traffic urban roads. Under almost all scenarios modelled, stronger pavements were needed, particularly for flexible pavements with poor quality subgrade. Larger and heavy Trackless Tram vehicles require stronger road pavement designs and for even the smaller three-module Trackless Tram on flexible pavements at light load levels, a more frequent service will require a 9.5% increase in pavement thickness compared to a lower frequency service. Implications of the research for future research and practice are discussed.

1.Introduction

A range of new bus technologies have the potential to provide the capacity and ride quality of Light Rail Transit (LRT), but without the cost of installing expensive new tracks and overhead wiring. Amongst these is the Autonomous Rail Transit (ART) vehicle developed by CRRC, the world's largest rail rollingstock manufacturer. Dubbed the 'trackless tram" this vehicle has battery power with or without stop recharge, optical guidance to assist platform docking, rubber tyres and "train-type bogeys with low set axles and hydraulic systems designed to prevent sway and bounce" (Newman et al. 2019). There is much interest in trialling trackless tram implementation in Australia because light-rail-like quality and capacity solutions seem feasible at substantially lower cost (Newman et al. 2018).
A major consideration for implementation of trackless trams is their impact on road pavements. CRRC claim the vehicle (fully loaded) weighs 51 tonnes (Newman et al. 2019), which is above the maximum allowed weight of a 6-axle semitrailer operating under Higher Mass Limit restrictions in Australia (National Transport Commission & NHVR 2020, p. 15; NHVR 2017). Road engineering suggests the damage done to pavements is governed by the '4th power of the

axle load. Hence an axle weight of 1,000kg is considered to cause 16 times the damage compared to one weighing 500 kg (IPWEA 2017). Vehicle weight is thus a valid concern.

So will road pavements need to be rebuilt to permit trackless tram operations? When researchers visited the Zuzhou operation in 2018; the manufacturer claimed the Trackless Tram "can be implemented very rapidly into most urban road systems without change and that after three years of trials there is no sign of road damage. Implementation is therefore possible to do in a weekend…"(p37, Newman et al. 2019).

This paper explores the road pavement impacts of the trackless tram and is structured as follows: the next section discusses the research context, including an outline of the relative merits of advanced bus designs like the trackless tram vs light rail. It also explores the relative weight of trackless trams compared to other vehicles and outlines independent findings on road pavement impacts of the existing trackless tram on a study tour to Zuzhou in 2019. The paper then describes a road pavement engineering model to estimate the likely impact of trackless trams under various scenarios on different types of pavement designs. Road pavement modelling[1] is then described. The paper closes with a summary of findings and a discussion of their implications for future research and practice.

2. Research context

2.1. Advanced bus designs vs light rail transit (LRT)

LRTs typically have better ride quality and passenger capacity than bus-based services. However, an LRT requires tracks, increasing the cost of construction and also limiting operational flexibility (Vuchic 2007, p. 541). Buses, in contrast, do not need special facilities and can traverse most roads because they are directly guided by the driver. There have been a number of specialised technologies developed that do provide automatic guidance (eg. Adelaide's O-Bahn system; various "tram on tyres" with mechanical guidance through a single rail; the optically guided Civis system in Rouen (Vuchic 2007, pp. 225-228, 447-455)), but these systems all retain bus-based suspension systems.

In contrast the recently developed ART Trackless Tram vehicle uses a railway bogie suspension system. It has been suggested that this makes it "potential game changer for cities struggling to attract investment in traditional light rail projects" (Newman et al. 2019), because it has a ride quality that is comparable to a tram, despite having rubber tyres and operating on a standard road pavement. It has an on-board battery and is guided by an automated optical system, but retains a steering wheel so that it can be directly guided by the driver if necessary. There is a three-module version with a passenger capacity of 250-300 and a five-module version that can carry up to 500 people (Newman et al. 2018, p. 83). There are lines in Zhuzhou, Yongxiu and Yibin, in China (Lawrie 2020) and proposals to adopt this technology in Australia and the USA (Chamberlain 2020; CRRC 2019). Table 1 details estimates of the relative costs of the Trackless Tram vs Light rail.

Table 1: Construction and Infrastructure Cost Comparsons per km ($AustM, 2018)

Cost Items	Light Rail	Trackless Tram	Difference
Manufacturer Costs (vehicles, recharge and comms systems)	$15M	$6M	-$9M (-60%)
Total Costs (incl road works, service relocation, design and management	$49-$100M	$16M	-$33M to -$84M (-67% to -84%))

Source: from Newman et al. (2018, p. 85) based on a consulting study of a project in Sydney, Australia

[1] The model was developed from an undergraduate student research project which provides input to this paper: (Pham, Currie & Reynolds 2021)

The potential savings are enormous; LRT is estimated to cost $49-100M per km[2] while trackless trams would be only $16M. Savings would be between $33M and $84M per km.

2.2. Trackless Tram Weight in Context

The three-module trackless tram vehicle has a fully loaded weight of 51 tonnes (Newman et al. 2019) and an unloaded weight of 32 tonnes (Rowland 2021). This makes it approximately twice as heavy as the limit for an articulated bus allowed to have general access to the road network in Australia (NHVR 2018). Comparisons of the three- and five-module ART Trackless Tram vehicle to the maximum mass and lengths of various bus and freight vehicles, the 24m Equi.City vehicle and selected Melbourne trams are shown in Table 2.

The three-module ART Trackless Tram has a similar weight to Melbourne's B2 class tram, but a similar length to an E class tram. When fully loaded it is approximately 5 tonnes heavier than the maximum mass limit allowed for a semi-trailer or other large freight vehicle to have general access to the Australian road network. Unfortunately, there is no publicly available information about the weight or length of the five-module version of the ART Trackless Tram. Scaling up linearly would suggest that it might be in the order of 50 tonnes unloaded, 85 tonnes with a full passenger load and approximately 50 metres long. This would give it a similar weight to the load limit that is set for a 12-axle A-double roadtrain, but with a length that is only slightly shorter than the maximum limit for the longest of vehicles allowed on Australian roads (an 18-axle ABB-Quad road train).

Light vehicles such as cars, vans and cars with trailers typically do little damage to road pavements. Pavement design therefore focuses on trucks, buses and other heavy (or 'commercial') vehicles. Because structural damage to pavements is cumulative, inputs to the design process are the load applied by each group of axles and the number of times the road will be subjected to such loadings over its design life (Moffatt 2017). Axle group load limits depend on the number of axles in a group, the number of tyres per axle, and whether the axle group is involved in steering. Trucks have a group limit of 9.0 tonnes with only one rear axle, 16.5 tonnes when there is a group of two rear axles, and 20 tonnes when there are three rear axles. However, the allowable load reduces if an axle group is involved in steering the vehicle, to 6.0 tonnes for one axle and 10 tonnes for dual axle steering groups. Buses are slightly different as they often have dual tyres, but the Trackless Tram does not have dual tyres (Rowland 2021). Instead it has 12 single tyres across 6 single axles with each axle putting a maximum load of 9 tonnes onto the road pavement.

As yet, it is unclear the extent to which Trackless Trams might be readily accommodated on all types of roads that transit services typically run on. Wong (2019) suggests that the "technology holds its greatest potential, and can readily be deployed along (the cross-town and orbital strategic corridors presently serviced by (for example) Metrobus in Sydney and SmartBus in Melbourne". While these sorts of services often run along the same sorts of major arterial roads that have significant volumes of trucks and semi-trailers, they also use lightly constructed roads to access residential areas, suburban railway stations and activity centres.

2.3. Pavement Performance of the Zuzhou Trackless Tram - 2019

A tour of the Zhuzhou trackless tram operation was undertaken in 2019[3] to explore a number of factors in the performance of the system including road pavement impacts. Despite claims made by CRRC in a visit by researchers the previous year (Newman et al. 2019), the 2019 visit shows clear evidence of road pavement 'rutting'; see Figure 1.

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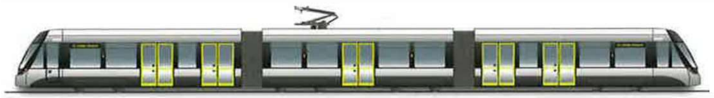
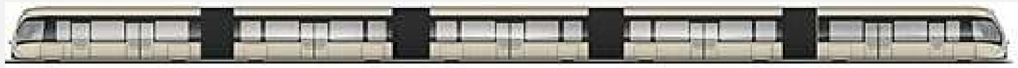
[2] Lawrie (2020) has estimated similar costs at $56 million per kilometre for the Canberra Light Rail system.

[3] The tour was hosted by CRRC and took place on July 3rd 2019 and was led by Prof Currie on behalf of the Monash Institute of Transport Studies, Sushou China campus and included delegates from Victoria, Australia interested in potential application of the technology.

Table 2: Mass, and length comparisons of selected vehicles (note: relative sizes of images are only approximately to scale)

Vehicle	Mass	Length	Indicative size and layout
Articulated bus	26 tonnes (maximum)	18.0m (max)	 Capacity approx. 130 passengers
Equi.City 'tram-bus'	24 tonnes (tare) 33.5 tonnes (approx.)(loaded)[1]	23.8m	 Capacity 137 passengers
6-axle semitrailer	45.5 tonnes (maximum under Higher Mass Limit restrictions)	19.0m (max)	
B2 class tram	34 tonnes (tare) 47 tonnes (approx.)(loaded)[1]	23.6m	 Capacity 182 passengers
Trackless Tram (3 Cr)	**32 tonnes (empty)** **51 tonnes (loaded)**	**31.6m**	 Capacity 250-300 passengers
7-axle B-Double	57 tonnes (maximum under Higher Mass Limit restrictions)	26.0m (max)	
E class tram	52 tonnes (tare)[2] 67 tonnes (loaded)[1]	33.5m	 Capacity 210 passengers
Trackless Tram (5 Cr)[3]	**50 tonnes (approx.)(tare)** **85 tonnes (approx.)(loaded)**	**50m (approx)**	
12-axle A-double	90.5 tonnes (maximum under Higher Mass Limit restrictions)	36.5m (max)	
18-axle ABB-Quad	135.5 tonnes (maximum under Higher Mass Limit restrictions)	53.5m (max)	

Sources: Choo and Yarra Trams (2020, p. 23); Newman et al. (2019); NHVR (2017, 2018); Rowland (2021); Sustainable Bus (2019); Van Hool (2020); Vuchic (2007, p. 213); Wilson and Budd (2014).

Notes: [1]Assuming 70kg/passenger (as per Rowland (2021)). [2]Source Wilson and Budd (2014),but Choo and Yarra Trams (2020, p. 23) state 46 tonnes. [3]Estimate based on scaling up 3-module vehicle by 60%. This might suggest a passenger capacity of 480, which is similar to the crush load of up to 500 reported by Lawrie (2020).

Figure 1: Photographs of Road Pavement 'Rutting' – Zhuzhou China Trackless Tram

The examples shown in Figure 1 suggest a deterioration of the road pavement surface due to the weight of the vehicle. We observe also that the area shown is the 'turnaround' zone at the northern terminus of the route where passenger loading is likely to be zero or very light. Hence it is likely the vehicle is at its lowest weight, not its highest weight at this point.

The road pavement rutting problem was pointed out to representatives of the manufacturer during the tour, who acknowledged the problem. They stated that the Zhuzhou implementation had been 'fast tracked' due to imminent scheduling of a major international sporting event where the service was to be showcased. As a result road pavements were not strengthened. They also stated that future implementation would include works to strengthen road pavements.

3. Road Pavement Engineering Modelling

This section outlines the road pavement engineering modelling used to estimate pavement impacts of the trackless tram. The focus is on understanding how road pavement performance is influenced by heavy vehicles like the trackless tram, rather than a detailed explanation of the formulae applied in the model. However some of the theory behind the modelling is explained to aid understanding of the issue.

3.1. Objectives

The modelling aimed to assess the depth of road pavement required to carry a trackless tram under a range of scenarios. Scenarios explore the relative effect of passenger loading and hence vehicle weight, as well as the effects of service frequency, which impacts the number of times the weight of the vehicle impacts the road surface during the lifespan of the road pavement. In addition the modelling sought to explore these issues for different types of road pavement design including both structural design and subgrade quality.

3.2. Theory

Modelling is based on the procedures and standards of road design and performance outlined in the AustRoads *Guide to Pavement Technology Part 2, Pavement Structural Design* (Moffatt

2017). The performance of road pavements in bearing the weight of vehicles varies significantly with both the general type of road construction as well as the quality of the 'subgrade' underneath the road pavement. In practice these conditions are very site specific. Actual performance modelling requires a site survey in almost every case. For this reason it is difficult to generalise actual performance of some road pavement types. For example major arterial roads typically have multiple asphalt surface courses applied over time of varying thickness. This complicates modelling and generalisability of a model for this type of road.
We have therefore focussed the modelling on two types of road pavements with less complex performance dynamics. This includes **flexible pavements** with a thin asphalt wearing course above a granular base/sub-base material; and **rigid pavements** consisting of a concrete base and subbase material. Flexible pavements with a thin wearing course are typical in cities for local access roads that do not cater for large volumes of heavy vehicles. However the potential for such roads to be used to operate trackless trams is very likely.
Flexible pavement is typically made up of a bitumen or asphalt wearing surface on top of base and subbase layers, and the (natural) subgrade. The purpose of the wearing course is to protect the granular material and to provide a trafficable surface. The base and subbase act to transmit the applied axle load to the subgrade and spread the force over a greater area so that it can be carried without failure. A weaker subgrade or a greater load, therefore, will require a thicker pavement to spread the load to a greater area.
The performance of a given road pavement over its design life is largely a function of: i) the thickness of the pavement materials; ii) the quality of the subgrade; and iii) the traffic load. The inter-relationships between these three factors for flexible pavements with thin bituminous surfacing can be determined using the empirical design chart shown in Figure 2.

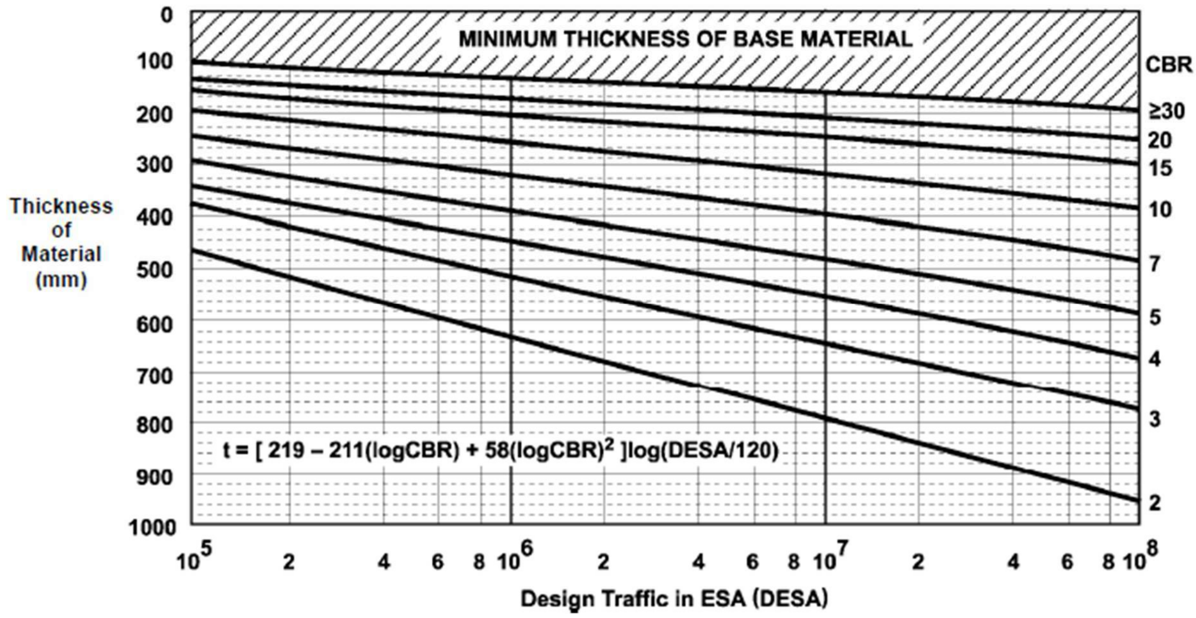


Figure 2: Design chart for flexible pavements with thin bituminous surfacing. Source: Moffatt (2017).

i. Thickness of pavement materials - the depth of the base and sub base.

ii. Quality of subgrade materials - a commonly used measure of the strength of a pavement or subgrade material is the **California Bearing Ratio** (CBR)(Y2 axis in Figure 2). The subbase can typically use a material with a lower CBR than the base, but the total required thickness of the pavementment base and subbase for a set traffic loading will be determined by the CBR of the subgrade. To simplify the model used in this research it is only this total pavement thickness (base plus subbase) that is reported.

iii. Traffic load - the load of traffic a road has to handle over its design life is measured using a standardised measure called the **Design Equivalent Standard Axles**

(DESA). An Equivalent Standard Axle (ESA) is the estimated structural damage done by "a single axle with dual tyres (SADT) applying a load of 80kN to the pavement" (Moffatt 2017). The Design Equivalent Standard Axles is a measure of the aggregate number of these experienced by a road over its design life. Figure 2 shows the **Design Equivalent Standard Axles** (DESA) on the x-axis as an input to the pavement thickness calculations.

A pavement might be expected to be subjected to hundreds of millions of ESAs over its lifetime. Figure 2, however, shows an upper limit of 10^8 ESA for which the empirical chart for granular pavements with thin bituminous surfacing is valid. Beyond a certain level of design traffic there is a need to consider issues related to the cracking of an asphalt surface under fatigue for which mechanistic-empirical procedures, based on calculating strains within the materials using structural mechanics methods need to be used (Moffatt 2017, p. 121). These mechanistic-empirical procedures are also used for pavements that use thicker layers of asphalt to provide structural strength, or that have asphalt for the full depth of the pavement. While this type of road construction is typical on major arterial roads and freeways, the mechanistic-empirical calculation procedures are beyond the scope of what can be incorporated into the generalised model developed in this research. However, the developed model does include calculation of thickness for rigid (concrete) pavements, based on the 19-step calculation procedure shown in Moffatt (2017, p. 133).

3.3. The Model

The model is an excel spreadsheet. It takes inputs related the subgrade's CBR, the desired design life of the road and, for rigid pavements, whether or not there is a concrete shoulder. All other calculation inputs, such a lane allocation factors and traffic mix, are based on those suggested in Moffatt (2017). For the ART Trackless Tram itself, the model's inputs include: the number of times that the vehicle will pass per day (service frequency); and the number of axle groups and the average load axle group load (a function of vehicle design and passenger loading). The model also considers pavement performance of a general traffic (no trackless tram) scenario to illustrate the relative impact of trackless trams. For this scenario, inputs include the Annual Average Daily Traffic (AADT) volumes, number of traffic lanes and the percentage of heavy vehicles so a comparison can be made to the pavement thicknesses required prior to a traffic lane being converted to exclusive transit use.

Based on this information the model outputs the DESA and the design thickness for both the flexible (thin wearing surface) and rigid (concrete) pavement options. Another input allows the user to set an existing thickness for a flexible pavement with a thin bituminious surfacing and calculate the expected pavement lifespan. In this analysis we focus on pavement surface thickness requirements the typical design lifespan of a road.

3.4. Modelling Scenarios

Two main scenarios are modelled: 1. No Trackless Tram – general road traffic; and 2. Trackless Tram – separate right of way.

1. No Trackless Tram – General Road Traffic Scenario

To provide a comparison to existing conditions, prior to the introduction of an ART Trackless Tram, the model has been run to calculate DESA and design pavement thickness for traffic only. Table 3 shows typical road types, lanes and traffic volumes, and these have been used as the basis for comparison. Morgan and Young (2017, p. 961) suggest that about 10% of the traffic that urban arterials carry on average over a day is commercial vehicles, and this value has been adopted as the model input throughout.

2. Trackless Tram – Separate Right of Way Scenario

Clearly, the specific service frequencies and subgrade soil, expected passenger loadings, and the volume and make-up of existing traffic will vary from site-to-site.

Table 3: Road types, typical lanes and traffic volumes (one-way)

Road type	Strategic arterial	Primary arterial	Secondary arterial	Collector	Local
Lanes	1 to 3	1 to 3	1 to 2	1 to 2	1
Daily traffic volumes	Generally 20,000+	May exceed 20,000	Up to 12,500	Up to 5,000	Up to 2,500

Source: Auckland Transport in Delbosc, Young and Brindle (2017, p. 129), converted from 2-way.

However, this research aims to gain a general understanding of the range of pavement thicknesses that might be needed to accommodate an ART Trackless Tram, rather than prepare a specific design for a case study site. As such, inputs used to produce the model output reported in the following section have been based on the following: typical CBR values range as low as 2 for poorly drained silt or plastic clay to up to 18 for sand (Moffatt 2017, p. 42), and output for both extremes are reported in the following section. A 30-year design life has been adopted, given that typical pavement design life is 20-40 years for flexile pavements and 30-40 years for rigid pavements (Moffatt 2017, p. 96). Model results are reported for a range of 40 to 120 average daily trips by the ART Trackless Tram service[4].

Another issue is the average axle loading that the Trackless Tram might apply, given that in the order of 35-40% of its maximum weight is passengers. Axle loading might therefore only be 9 tonnes at the busiest point along a line during peak times. To give an indication of the range of pavement loadings average axle load of 6 and 8 tonnes per axle, representing average occupancies in the order of 15-20% and 70-75% respectively are shown in the next section.

4. Results

Results are presented in terms of traffic load (DESA) estimates (Figure 3) and then design pavement thickness required (Figure 4) for the two sets of traffic and trackless tram scenarios.

Figure 3 shows model output for traffic load measured in terms of Design Equivalent Standard Axles calculation for the (1) Traffic only scenario and (2) Trackless Tram scenario. The traffic scenario (scenario 1) is shown for three sets of traffic volume and lane configuration combinations, assuming no Trackless Tram and with a 10% commercial vehicle share. For scenario 2, three separate sets of vehicle and passenger loading arrangements are shown for the Trackless Tram options: (1) a 3-module ART Trackless Tram with a 6-tonne average axle load (green) and with (2) a 8 tonne average axle load (orange); and (3) a 5-module version with an 8-tonne average axle load (red). These all assume the Trackless Tram operates in its own lane.

Figure 4 indicates that the Trackless Tram vehicle is likely to substantially increase the loading that a road pavement might be subject to over its design life compared to typical traffic roads:

- Even when operating at only 40 trips a day (low frequency) and at low average passenger loadings (average 6 tonne axle loads) the vehicle is expected to apply 8.63×10^6 ESAs over a 30-year pavement design life. This is approximately 14 times greater than the design loading of 6.15×10^5 ESAs per lane that the model output for high traffic load road option.
- The highest traffic loading for a 5-module ART operating at an average of 8 tonnes per axle across 120 trips per day, is 1.36×10^8 ESAs. This is a load which is 15.8 times greater than the 3-module, 6-tonne scenario and 221 times greater than the high traffic only road scenario.

[4] Indicative low frequency service of 30min headways 5-7am and 6-11pm (off-peak), 15mins headways 7-9am (peak) and 4-6pm and 20min headways 9am-4pm (inter-peak) results in 51 daily trips. A high frequency option of 20min (off-peak), 5 mins (peak) 10min and 5mins (interpeak) results in 111 daily trips.

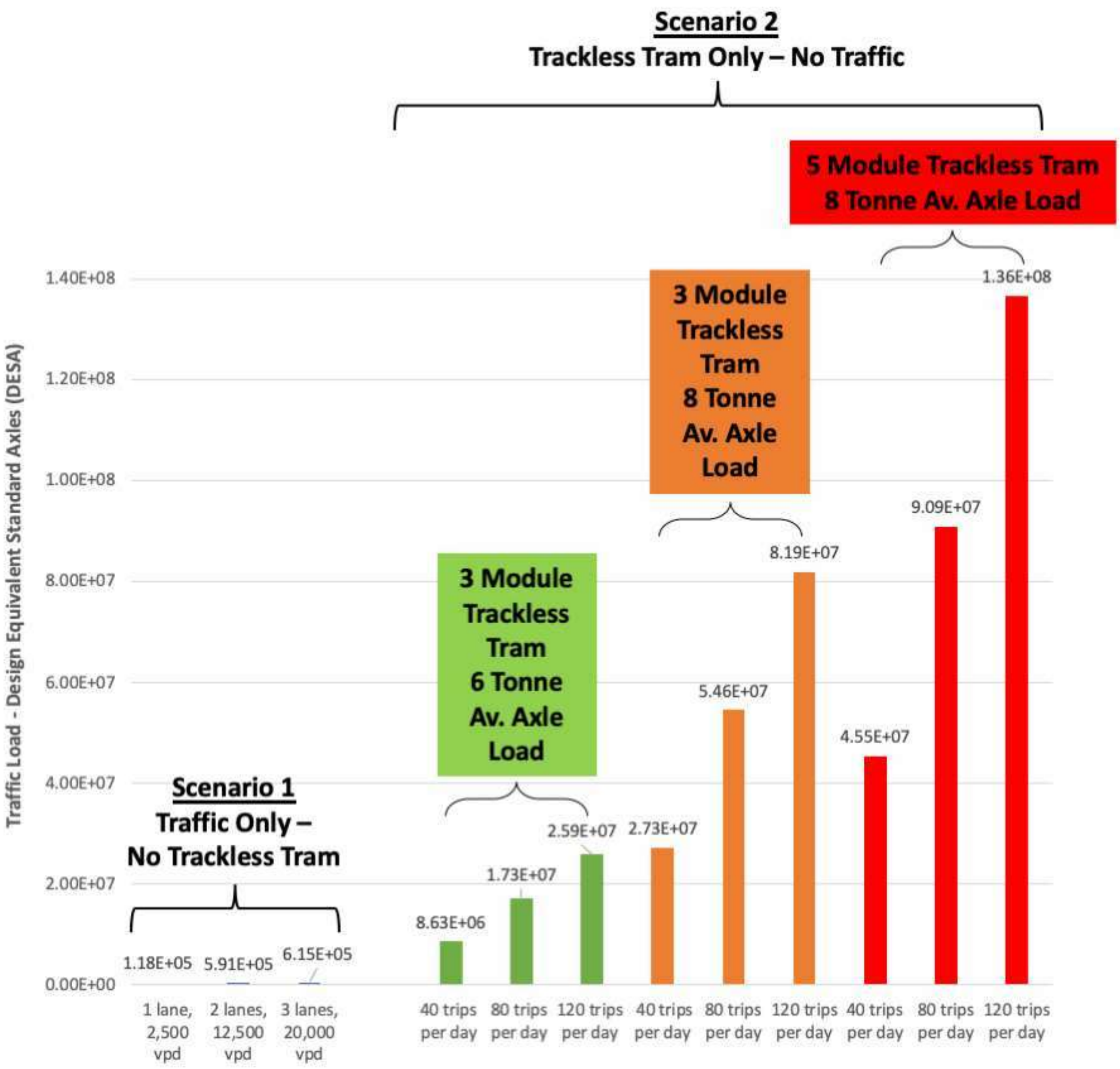


Figure 3 Traffic Load (Design Equivalent Standard Axles) Estimates for Model Scenarios

Figure 4 indicates that:

- Subgrade quality: i) Pavement thickness required to carry traffic loads varies most by the quality of the subgrade under any scenario combination. ii) This variation is largest for flexible pavements, which need to be substantially thicker for poor subgrade quality contexts. iii) For rigid pavements, required pavements need to be thicker for poor quality subgrade but not by much.
- Scenario Modelling – Poor Quality Subgrade: i) for Flexible Pavements, a substantially thicker pavement is needed for Trackless Trams over the 30-year life span of the road. Compared to the high traffic scenario (596mm) pavement depth needs to be increased to between 781mm and 945mm, depending on the scale of traffic load. For the lowest load trackless tram option design (3 module, 6 Tonne average axle load), an increase in service frequency means that a flexible pavement road would need to increase its thickness from 781mm for a 40 trip per day service to 857mm for a 120 trip a day service (+9.5%). ii) For Rigid Pavements, thicker pavements are also needed for the Trackless Tram options compared to the Traffic only scenario, but increases in thickness are much smaller; compared to the high traffic scenario (325mm), Trackless Tram only rigid pavement roads would need to increase to between 350mm and 380mm depending on option. Interestingly no increase is needed for the 3-module, 6-tonne axle load option at only 40 trips per day.

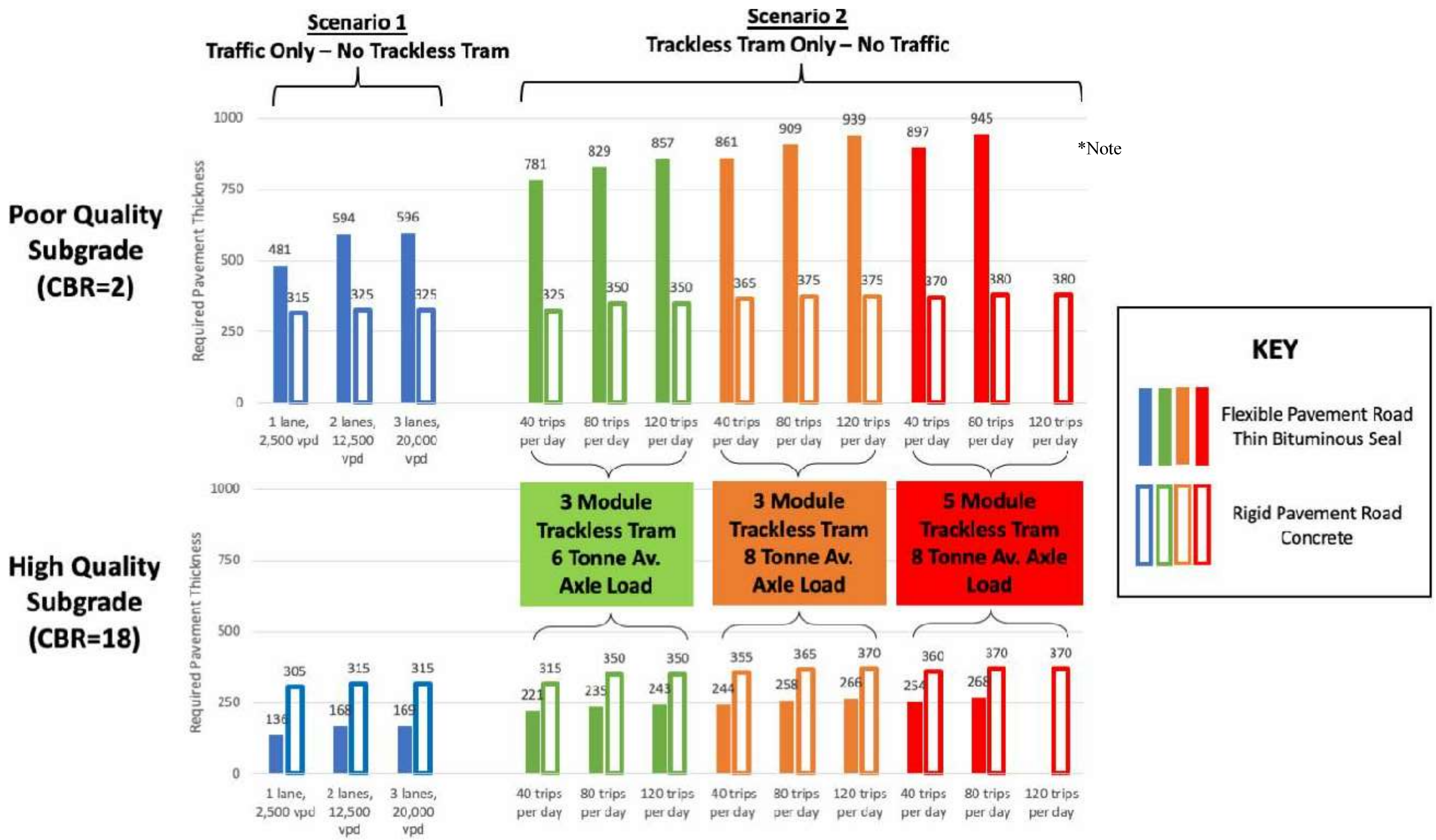


Figure 4 Design pavement depth for subgrade CBR = 2 (poorly drained silt or plastic clay).

*Note: Flexible pavement depth for 5-module Trackless Tram - 120 trips not shown as DESA of 1.36×10^8 ESAs is beyond the limits of Figure 5.

- Scenario Modelling – High Quality Subgrade: i) Flexible Pavement thicknesses are less than those required for Rigid Pavements. ii) For Flexible Pavements, thicker pavements are needed for all the Trackless Tram options. Compared to the high traffic only scenario (169mm), pavement depth needs to be increased to between 221mm and 268mm depending on the scale of traffic load. For the lowest load trackless tram option design (3 module, 6 Tonne average axle load), an increase in service frequency means that a flexible pavement road would need to increase its thickness from 221mm for a 40 trip per day service to 243mm for a 120 trip a day service. iii) For Rigid Pavements, thicker pavements are also needed for Trackless Tram options compared to the Traffic only scenario. However, increases in thickness are again much smaller than for Flexible pavement roads; compared to the high traffic scenario (315mm), Trackless Tram only Rigid pavement roads would need to increase to between 350mm and 370mm depending on option. Interestingly no increase is needed for the 3 module, 6 tonne axle load option at only 40 trips per day. iv) For the high-quality subgrade tests, Trackless Tram impacts on required pavement thickness don't vary much by subgrade quality.

5. Discussions and Conclusions

This paper explores the road pavement impacts of new Trackless Tram bus technologies. While Trackless Trams have significantly lower estimated construction and infrastructure costs compared to Light Rail because they can use existing roads and don't need rail tracks it has refuted claims from the manufacturer that existing Trackless Tram operations have not caused road pavement damage. Rather damage has been observed and claims for a 'weekend' system construction period using existing road pavements seem very optimistic.

So, will road pavements need to be rebuilt to permit trackless tram operations? This research suggests this is likely, particularly for the pavements typically used where heavy vehicles are not commonly deployed. However, this research is limited by the relatively sparse information that is available about the ART Trackless Tram itself. This is perhaps not surprising given its recent development and that this has occurred overseas. Further research might revisit this topic when more information is available about the vehicle, especially the 5-module variant, as well as examining road pavements where multiple asphalt layers contribute to structural strength, which are typical of major arterial roads that do already carry large volumes of heavy vehicles. Neither has the research described in this paper considered recent developments in pavement technology such as semi-flexible pavements (Hassani, Taghipoor & Karimi 2020), or situations where road traffic and Trackless Trams would share lanes. As such, future research might consider a much greater range of pavement scenarios than has been included in this study.

Will pavement strengthening reduce the construction and infrastructure cost advantages that the Trackless Tram has compared to Light Rail? We don't think so. Newman et al. (2018, p. 85) show an estimated cost of $10M per km (excluding vehicle costs) for Trackless Trams versus $34-85M per km (excluding vehicles costs) for LRT (Table 1). It is unclear how much allowance for roadworks is included in that $10M per km, but even if pavement costs prove high the Trackless Tram appears likely to still be much cheaper than LRT.
Where a route is to run along an arterial road already built for large volumes of heavy vehicles roadworks costs might be low, assuming that it is politically and practically possible to convert existing lanes to Trackless Tram use rather than having to add lanes through road widening. However, Trackless Trams would seem likely to often be introduced along roads servicing activity centres, shopping strips and other passenger generators/attractors, where conditions are likely to be more constrained, rather than along freight routes. Using asphalt overlays to increase pavement strength might not be possible in such locations because of a need to match

existing kerbs, footpaths and adjacent properties, meaning that pavements might instead need to be fully rebuilt. The extent and cost of such works appears likely to be highly dependent on project and site context, which suggests that there is a need to better understand the likely range of roadworks-related costs for Trackless Trams and how these compare to BRT and LRT. Review of the costs of previous road strengthening projects might be one avenue for future research. A better understanding will also likely develop through practice as planning studies begin to include Trackless Trams as an option and as the technology is implemented in more places. There may be a role for researchers to monitor, report and compare the costs developed in planning studies and construction estimates. This also suggests a need for research that constrasts Trackless Trams with BRT/LRT across a range of other issues including whole-of-life and economic costs, and how differing construction period lengths might influence the impacts on local businesses and other stakeholders when a new route is implemented.

While the ART Trackless Tram vehicle is an exciting development in on-road transit, it remains unclear whether its promises of high passenger capacities and low implementation costs will eventuate in reality over the mid-to-long term. It may be possible to drive these heavy vehicles along existing high-strength roads (that already cater for large volumes of heavy freight traffic), at least for a short period of time, without pavement failure. However, the modelling presented here suggests that many existing road pavements, particularly those with only thin seals and that do not accommodate overmass vehicles, may not be sufficient to support an ART Trackless Tram over a typical 30-year design life. While an ART Trackless Tram might be implemented "in a weekend" (Newman et al. 2019) by repurposing existing roads, the long-term viability of such an implementation is yet to be proven.

Acknowledgements

This paper is based on work completed for a final year engineering project by David Pham, with the topic being suggested by the RACV. Peter Kartsidimas and Joshua Chivers of the RACV both provided input during the course of the final year project. Mark Rowland (ARUP / Transport for NSW) also helped by providing details about the Trackless Tram vehicle, while David Sutcliffe (HDS Australia) provided insights about pavement strengthening works.

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