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Analysis of the Impact of New Generation Narrow-Body Aircraft on Flexible and Rigid Regional Airport Pavements

Greg White

School of Science, Technology and Engineering, University of the Sunshine Coast, Maroochydore, QLD 4558, Australia; gwhite2@usc.edu.au; Tel.: +61-400-218-048

Abstract: Airport pavements have always evolved to keep pace with the demands of new aircraft. As aircraft weights and tyre pressures increase, stronger, new pavements are designed and existing pavements are rehabilitated or upgraded. The narrow-body commercial jet aircraft, including the A320 and B737 families, are examples of aircraft that have retained the same number of wheels, with the same wheel spacing and the same wingspan, but have increased in weight and tyre pressure by approximately 50%. This places significant demand on airport pavements that were designed for the lighter variants but now face the introduction of the newer, heavier and more demanding variants. This research quantified the impact of the new A320 and B737 narrow-body aircraft variants on rigid and flexible regional airport pavements, where these are the critical aircraft, as well as demonstrating the importance of understanding the operational weight limitations of these aircraft, which is often well below the published maximum weight. Within the context of the pavements considered, the additional pavement thickness required for the heaviest aircraft variants, compared to the lightest variants, was 51%. Based on four examples from real regional airports in Australia, it was found that the additional embodied carbon associated with these new aircraft variants was 2.1–85.3 kg·eCO_2/m^2 of pavement, while the additional financial cost was AUD 6–219/m^2 of pavement. It was concluded that airport pavement thickness designers must challenge the weight of the design aircraft and not take the simple and conservative approach of adopting the maximum weight of the heaviest variant within each aircraft family. By doing so, significant additional pavement thickness will be constructed for no practical benefit, creating an environmental (embodied carbon) and economic (financial cost) burden.

Keywords: airport; pavement; narrow body; aircraft; thickness; cost; carbon

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1. Introduction

Airport pavements have always evolved to keep pace with aircraft developments. When the Wright brothers achieved the first airplane flight in 1903, airport pavements were not an issue, as the aircraft were light enough and robust enough to operate from any relatively flat and cleared paddock [1]. Similarly, during World War I, aircraft played only a minor part and generally operated on unprepared ground in cleared fields. However, military aircraft played a more significant role in military operations during World War II, including long-range surveillance in the Pacific, aircraft carrier-based fighter operations and long-range bombing raids. By the end of World War II, aircraft had become too heavy to continue to operate on unprepared ground, and this prompted the first significant interest in airfield pavement design [1].

Aircraft technology also developed during World War II, which formed the basis for the significant advances in commercial aircraft that have occurred since that time. Subsequent aircraft technology development was also fueled by the Cold War between the United States of America (USA) and the Union of Soviet Socialist Republics. For example, between the early 1940s and the early 1950s, military aircraft tyre pressures doubled from around 0.6 MPa to around 1.2 MPa [2]. At the same time, commercial airlines were established and brought air travel to the general population, with many of the world's current major airlines being formed between 1919 and 1930 [1].

One significant step in commercial aircraft growth was the DC-8-50, first introduced in 1958. At the time, this was the most damaging of all commercial aircraft with 19 tonnes of wheel load on 1.35 MPa of tyre pressure and closely spaced wheels. Tyre pressures and wheel loads subsequently increased incrementally as new aircraft were developed and entered service [3,4]. This trend has not abated, and the latest aircraft models are designed to minimise fuel consumption per passenger per distance flown, with the B777-300ER, A350-600, B787-8 and A350-900 currently being some of the most demanding aircraft in the world [5]. This is often achieved by heavier aircraft weights supported on the same or fewer main gear wheels. In response, newly constructed pavements must be designed to be stronger than in the past, and existing pavement often requires strengthening to meet the increased demand of modern aircraft [6].

Although many of the new aircraft models mainly impact international airports and their pavements, regional airports are also affected. For example, in Australia, many regional airports were developed for military aircraft and then supported commercial F27 or B727 aircraft in the decades following World War II [1]. In current times, the Saab 340B and Dash 8-Q400 are the main regional aircraft for the smaller regional airports, while the narrow-body A320 (A318, A319, A320 and A321) and B737 (−100 to −800 variants and MAX) families of aircraft operate into many of the larger regional airports [7]. The A320 and B737 families are similar but each contains a significant range of aircraft, with the heaviest of each family more than 45% heavier than the lightest variant within each family. In terms of the future, Qantas has ordered up to 109 A321-XLR aircraft [8] to be delivered starting in 2025, while Virgin Australia has ordered 25 B737 MAX 10 aircraft, expected to arrive starting in late 2023 [9]. These aircraft are expected to replace longer sector and higher demand narrow-body domestic services within Australia, as well as some limited point-to-point international services. The A321-XLR and B737 MAX 10 are significantly heavier than the previous variants within their respective aircraft families. Although this will not trouble the major capital city airports that already service B777, A350 and other wide-body aircraft, they have the potential to significantly impact larger regional airports for which the B737/A320 are currently the critical aircraft for pavement strength. Similarly, for airports that service the larger A330 aircraft, the A321-XLR and B737 MAX 10 also have the potential to impact existing pavement adequacy and the design of new or existing rehabilitation designs.

The aim of this research was to quantify and analyse the effect of new variants of narrow-body aircraft on regional airport pavements. The A321XLR and the B737 MAX 10 aircraft were focused on, and the analysis considered both flexible and rigid aircraft pavement types. Although presented within the context of regional Australian airports catering to B737/A320-sized aircraft, the same principles apply to similar regional airports in other countries, and other airports that experience incremental increases in aircraft loading over time. It is intended that this work will allow practitioners and researchers to understand the potential impact of new and heavier aircraft variants on existing and new aircraft pavement structures. By quantifying these impacts in terms of additional financial cost and embodied carbon, it is intended that unnecessary conservatism associated with the adoption of the heaviest aircraft variations in all cases, will cease and the waste associated with unnecessarily conservative pavement thickness determination will be avoided in the future. Researchers may also use or adapt this novel approach to provide quantified financial cost and embodied carbon values associated with other pavement designs to place their research into a practical context for practitioners and decision-makers alike.

2. Background

2.1. Aircraft Pavements

Aircraft pavements are designed using the same principles as roads and other pavements. However, there are a number of differences that reflect the lower frequency of higher magnitude loads, compared to road pavements, as well as the low tolerance of aircraft to uneven pavement surfaces, free-standing water on pavement surfaces and pavement-generated loose material that can damage aircraft engines [1,10].

Like roads and other pavements, aircraft pavements are generally categorised as rigid, flexible or composite. Rigid pavements are characterised by a thick concrete base that bends or flexes to accommodate stress. A granular or stabilised sub-base is usually provided but does not significantly contribute to the strength of the pavement [11]. In contrast, flexible pavements predominantly comprise a granular base and sub-base layers that are designed to vertically deform under load, spreading the load across a greater area until the stress is reduced adequately to allow the subgrade to not rut excessively under repeated loading. The surface is usually bituminous and a thin (<80 mm) or thick (>80 mm) asphalt concrete surface is commonly provided [10].

When deciding whether to construct a new pavement as a rigid or flexible structure, an airport commonly considers the relative cost, the expected traffic loadings and the local environmental conditions [12]. Rigid pavements are more commonly used in hot climates, where asphalt is prone to softening, and in slow-moving aircraft areas, where asphalt is prone to shear creep [13] and exposed to damaging hydrocarbons during aircraft refuelling [14]. The relative cost of rigid and flexible aircraft pavements is highly dependent on the analysis period and key assumptions regarding the end-of-life condition, with rigid pavements being either slightly less expensive or significantly more expensive than structurally equivalent flexible pavements on a whole-of-life basis, depending on the assumptions made [12].

Regardless of the type of pavement selected, all new pavements are designed, and existing pavements are periodically rehabilitated, particularly when a strength increase is required for larger and more demanding aircraft operations [1]. Although thickness determination is an important element of the design process, it is only one element. Material selection and pavement composition, subgrade preparation and granular layer-proof rolling during construction are also important elements for flexible airport pavement design practice [15]. Similarly, concrete strength, slab size, sub-base materials, as well as joint types and details are all important elements of rigid airport pavement design practice [16].

2.2. Pavement Thickness Determination

As stated above, thickness determination is an important element of any aircraft pavement design. Although pavement thickness determination was empirical in origin [17], in modern times it is a mechanistic-empirical process whereby the stresses and strains are theoretically calculated at pre-determined critical locations in the pavement, and then related to an allowable number of repetitions of the load via empirically derived failure criteria, also known as transform functions or performance relationships [18]. The mechanistic calculation of the theoretical stresses and strains in a pavement's structure has also evolved over time. Initially, simple mathematical models were necessarily used, due to the lack of computation power required for more sophisticated solutions [1]. However, as computer power has increased with time, multi-layer, linear elastic and finite element solutions were introduced.

In modern times, aircraft pavements are usually designed with specific software, most of which are layered elastic in nature and include [1]:

1. Failure criteria that better reflect aircraft loading and pavement performance expectations;
2. Materials that reflect those commonly specified for aircraft pavement construction;
3. The ability to model different aircraft separately, without the need to convert different aircraft to an equivalent number of passes of a reference aircraft;
4. Consideration of one-, two-, four- and six-wheeled aircraft landing gear arrangements;
5. Statistically-based lateral wandering of aircraft across the width of the pavement.

There are many software choices available for the design of rigid and flexible aircraft pavements. In Australia, the software APSDS [19] is used for flexible pavements, and Alize [20] is used for all pavement types in France, while PCASE [21] is used by the military in the USA. However, it is commonly accepted that FAARFIELD [22], provided by the Federal Aviation Administration (FAA) of the USA, is the most widely and commonly used software around the world for airport pavement thickness determination.

2.3. FAARFIELD Software

The chart-based methods of airport pavement thickness determination were largely replaced by computer software in the 1990s [23]. The FAA first introduced the software known as LEDFAA in 1995, which used layered elastic analysis [24]. LEDFAA was used in parallel to the FAA's chart-based methods and was mandatory for pavement designs including the then newly introduced six-wheel main landing gears associated with the B777 and A380 aircraft [25]. FAARFIELD (v1.3) subsequently replaced LEDFAA when the FAA's associated design guidance was updated in 2009 and used layered elastic analysis for rigid and flexible pavements, and an additional finite element analysis for rigid pavements [26]. The 2009 edition was the first not to include historical chart-based design methods, completing the FAA's transition to software-based thickness design of aircraft pavements. However, the failure criteria in FAARFIELD 1.3 were developed to retain general agreement with pavement thicknesses determined by the previous design-based charts, in which the FAA had significant experience and a high level of confidence.

A major revision, known as FAARFIELD 1.4, was released in 2016, corresponding to another major update to the design guidance [27]. Significant changes were made to the rigid pavement design module, reflecting analysis of the result from additional full-scale tests performed by the FAA, known as construction cycles CC2 and CC6 [28]. The changes included improved finite element meshing, changes to granular sub-base modulus assignment, as well as changes in the conversion between subgrade CBR, the modulus of subgrade reaction (k-value) and the elastic modulus [29]. FAARFIELD was later updated to version 2.0, which included a new user interface and pavement strength rating calculations [22]. However, the pavement thicknesses were not changed from the previous version 1.4 [30].

Current Australian airport pavement design practice is to use the FAA's FAARFIELD 2.0 [22] software for thickness determination. The use of the FAA's software generally reflects its availability, user-friendliness, inclusion of most modern aircraft models and the incorporation of the results from the most recent full scale pavement testing [31]. FAARFIELD 2.0 was used for all pavement thickness determinations in this research. Like other practical pavement design software, FAARFIELD uses a simplified pavement structure and analysis system that does not take into account the visco-elastic nature of bituminous materials, the changes in material properties over time or the dynamic loading effects associated with aircraft taxiing and landing [22].

Sensitivity analyses of pavement thickness determination performed on FAARFIELD 1.4 determined that rigid pavement slab thickness was most sensitive to aircraft weight and concrete strength, with subgrade support, aircraft load repetitions and aircraft tyre pressure being significantly less influential [11]. Similarly, for flexible airport pavement thickness, the most sensitive input parameters are aircraft weight and subgrade bearing capacity, with aircraft load repetitions and aircraft tyre pressure again being less influential [32]. In light of the high sensitivity of both rigid and flexible airport pavement thickness to aircraft weight, incremental increases in aircraft size with the same general landing gear arrangement is important for both new airport pavement thickness design and for existing airport pavement rehabilitation.

The characteristics of any given aircraft that must be defined, either directly by the designer or indirectly by the selection of the aircraft type/model/variant, and generally include [27]:

- Load repetitions over the structural design life of the pavement;
- Total aircraft weight and the portion of that weight carried by the main landing gears;
- Tyre inflation pressure for the main landing gear wheels;
- Main landing gear configuration, including the number and spacing of wheels.

Different software accepts these aircraft characteristics differently. For example, APSDS requires the number of load repetitions to be entered explicitly, while FAARFIELD allows for an annual number of departures, the structural design life and an annual growth rate to all be input separately.

2.4. Aircraft Classification Numbers

Some airport pavements are designed for large international aircraft but many regional airport pavements are designed for the smaller aircraft that operate into that airport. To avoid inadvertent overloading of these pavements, a pavement strength rating system was developed by the International Civil Aviation Organisation (ICAO) in 1981 [33]. This system includes a method to calculate a value, known as the Aircraft Classification Number (ACN) for every aircraft. The ACN represents the relative effect of that aircraft, at that weight and tyre pressure, on a pavement [1]. Because rigid and flexible aircraft pavements respond to loads differently, the same aircraft will have a different relative effect; therefore, there will be a different ACN for a flexible pavement and a rigid pavement. Furthermore, because ACN values reflect the number and spacing between the main landing gear of large aircraft, the thicker the pavement, the more the wheels interact. To ensure the ACN values reflect the increased importance of wheel interaction at the top of the subgrade of thicker pavements, which is mainly a function of the subgrade support condition, the ACN values are calculated for four subgrade categories, referred to as A (high strength), B (medium), C (low) and D (ultra-low strength). The system also requires airports to publish Pavement Classification Numbers (PCNs) for their runway, against which each aircraft ACN is compared. Aircraft with an ACN lower than the PCN can operate without restriction and are not expected to overload the pavement. This gives rise to the common term; the ACN–PCN system. However, an aircraft with an ACN value that exceeds the PCN of the runway requires permission prior to operating, usually referred to as a pavement concession [1]. There is also a second check of the aircraft tyre pressure, against a tyre pressure rating for the surface, intended to protect fragile surfaces from high tyre pressures, but this element of the system was shown to be ineffective and requires improvement [34].

The ACN–PCN system has remained largely unchanged since its introduction. Minor changes to the ACN values of four- and six-wheeled aircraft, to better reflect full-scale testing performed by the FAA in preparation for the B777 and A380 aircraft, were introduced in 2008 [25]. Also, the tyre pressure category limits were increased to reflect new aircraft models and variants in 2013 [4]. However, aircraft pavement design evolved, including the introduction of mechanical-empirical methods, based on layered elastic and finite element methods. This created occasional anomalies, whereby a pavement designed with a specific aircraft in the traffic loadings was subsequently rated by the ACN–PCN system with a PCN value lower than the ACN of that aircraft [1]. That meant that an aircraft that the pavement had been designed to accommodate, required a pavement concession to be allowed to operate, which is illogical. To mitigate this, a revised strength rating system, using an Aircraft Classification Rating (ACR) value compared to a Pavement Classification Rating (PCR), was developed by ICAO and is due to be implemented in November 2024 [35]. The system is largely a mirror of the ACN–PCN system but the ACR values are calculated using layered-elastic methods, resulting in much fewer anomalies between the design and the strength rating of aircraft pavements [30].

2.5. Regional Airport Pavements

Regional airports are generally located away from the State capital cities in Australia and the narrow-body B737/A320-sized aircraft are often the critical or near-critical aircraft operating into those airports. Regional airport pavements are predominantly flexible pavement structures with a thin bituminous wearing surface [36]. Although sprayed seals or chip seals are often used for smaller regional airport pavement that do not support jet aircraft, thin asphalt, typically 50–80 mm in thickness, is common for larger regional airports [10]. These flexible pavements are often constructed with marginal locally available granular materials and often have poor drainage characteristics [1].

The majority of regional airports in Australia are owned and operated by either local government organisations or private companies [36]. Furthermore, Australia does not subsidise the cost of new pavement construction or existing pavement rehabilitation works for privately owned airports, such as the airport improvement program in the USA [37]. Consequently, Australian airports are sensitive to the cost of constructing, upgrading and maintaining their airport pavements, the majority of which is recovered through airline landing charges, which is ultimately reflected in the cost of airfares paid by the travelling public [7]. As a result, providing economically efficient airport pavement assets is important to regional airports in Australia [38].

3. Methods

To analyse the impact of new variants of narrow-body aircraft on rigid and flexible regional airport pavements, a sequential research method was adopted (Figure 1). First the development of the aircraft variants often time is outlined, and their relative effect on aircraft pavement life is quantified before real-life examples of new pavement designs and existing pavement evaluations are presented as a series of case studies.

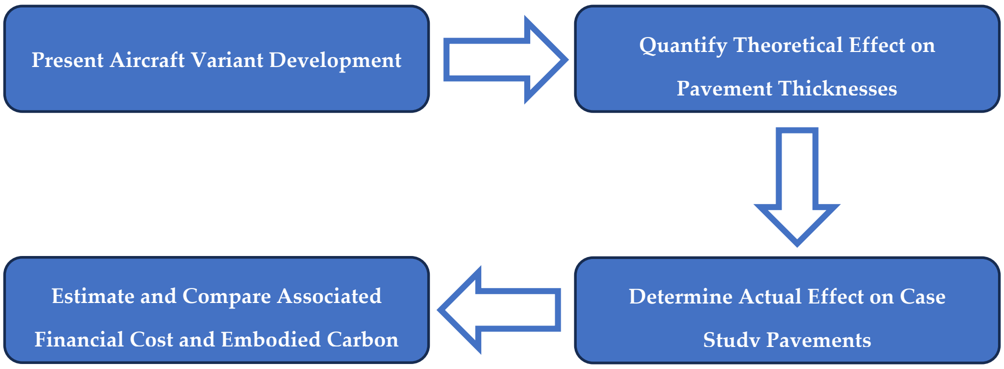


Figure 1. Schematic flow of research methods.

To analyse the growth of the aircraft variants within the B737/A320 narrow-bodied commercial jet aircraft families over time, the published aircraft maximum weight, main gear tyre pressure and approximate year of introduction were collated from publicly available sources, primarily from the FAARFIELD aircraft library [22] and the aircraft manufacturer's webpages [39,40]. Because different tyres and even different engines can affect the weight and tyre pressure of the same variant of aircraft, some sources publish slightly different weights and tyre pressures. Furthermore, aircraft are usually developed and introduced over many years. Therefore, the year of introduction of a specific variant can reflect the commencement of its development, the year of the first test flight, its certification by any aviation authorities, such as the FAA, or the year of first delivery to an operational airline. Consequently, the year of introduction of each variant can only be indicative. For each aircraft variant, the rigid and flexible pavement ACR values for ICAO subgrade category A and subgrade category D were also calculated.

FAARFIELD 2.0 was used to calculate the life, expressed as the CDF, and thickness of rigid and flexible aircraft pavement structures at typical subgrade support conditions. The composition of these pavements was selected to be typical of regional airports in Australia, New Zealand, the United States and the United Kingdom. Each pavement life and thickness were calculated for each A320 and B737 aircraft variant separately. It is acknowledged that FAARFIELD is generally not intended to be operated for single aircraft traffic loadings [27]. However, this is the only way to isolate the effect of the different aircraft variants [30].

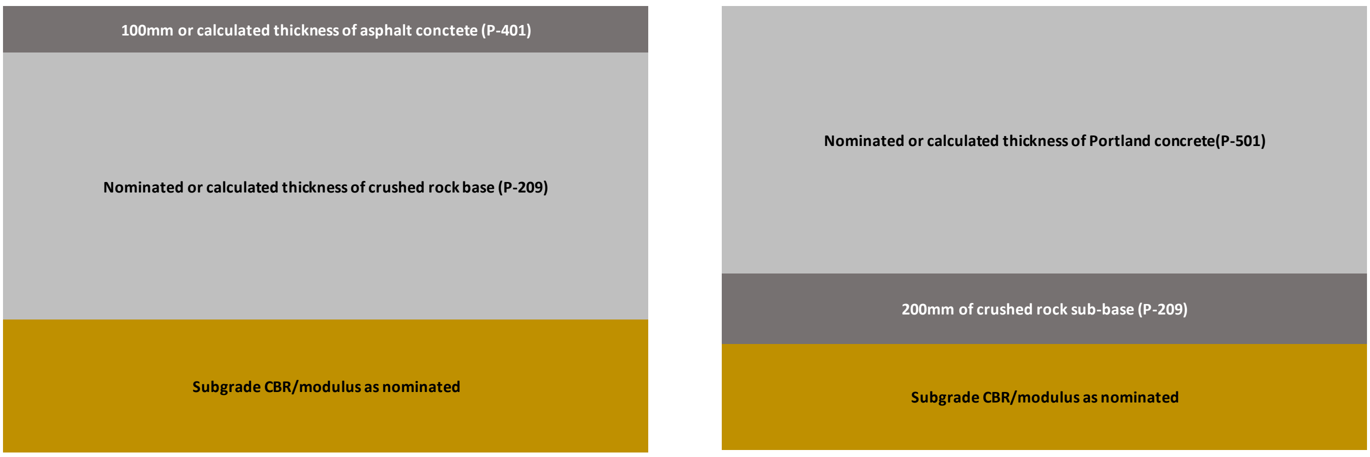
To reflect the typical range of subgrades, four subgrade conditions were considered, reflecting the standard subgrade California Bearing Ratio values for flexible aircraft pavement strength rating [33], with the subgrade condition characterised in FAARFIELD differently for the flexible and rigid pavements (Table 1). In all cases, 1200 annual departures of the applicable aircraft variant were assumed over a 20-year design life, without any growth in aircraft frequency. For the pavement life calculations, a thick and a thin pavement were adopted, and the cumulative damage value (CDF) [1,26] was determined. The CDF value reflects the portion of the theoretical structural life of the pavement that is consumed by the aircraft loading. A CDF value of 1.0 indicates an optimal pavement thickness, while a thicker or stronger pavement will have a CDF less than 1.0, and a thinner/weaker pavement will have a CDF greater than 1.0.

Table 1. Subgrade conditions and characterisation.

Subgrade Condition (California Bearing Capacity)	Flexible Pavement Characterisation	Rigid Pavement Characterisation
3%	31.0 MPa	18.3 kPa/mm
6%	62.1 MPa	31.4 kPa/mm
10%	103.4 MPa	46.8 kPa/mm
15%	155.1 MPa	64.2 kPa/mm

Note: In FAARFIELD, flexible pavement subgrade conditions are input as elastic modulus values, while rigid pavement subgrade conditions are input as a modulus of subgrade reaction, commonly known as the k-value.

For the pavement thickness calculations, the pavement compositions were selected to reflect airport pavement design practices in Australia and the USA (Figure 2). For the pavement life calculations, the life was calculated for a relatively thick and a relatively thin pavement (Table 2) on a CBR 6% subgrade condition. The thicknesses for 'thick' and 'thin' were selected subjectively, so that the lightest aircraft in each family (A318-100 std and B737-100) resulted in a CDF in the thin pavement of approximately 0.05, while the heaviest variants (A321 XLR and B737 10 MAX) resulted in a CDF of approximately 0.5 for the thick pavement.



(**a**) (**b**)

Figure 2. Schematic (**a**) flexible and (**b**) rigid pavement compositions.

Finally, examples of the practical effect of different aircraft variant assumptions on the design and rehabilitation of actual flexible aircraft pavements are presented. These include four flexible and two rigid pavements from real-life Australian airport pavement projects and include the estimates of the aircraft variants on the embodied carbon and financial cost associated with the increased pavement thickness.

Table 2. Fixed pavement layer thicknesses for pavement life calculations.

Pavement Type	Thick or Thin?	Pavement Layer	Layer Thickness
Rigid	Thin	Concrete slab (P-501)	300 mm
Rigid	Thick	Concrete slab (P-501)	425 mm
Flexible	Thin	Crushed rock base (P-209)	500 mm
Flexible	Thick	Crushed rock base (P-209)	700 mm

Note: Other pavement layers were fixed as per Figure 2.

4. Results and Discussion

4.1. Growth of Aircraft

The B737 family of aircraft commenced with the −100 and −200 variants in 1967 and now includes 14 main variants, including the B737 10 MAX, that is expected to enter service in 2024 (Table 3). The initial variants had a maximum mass of 50–53 tonnes, which has almost doubled over time to the expected 95 tonnes for the B737 10 MAX. The tyre pressures have similarly increased by more than 50% over the same time. By comparison, the A320 family of aircraft was first introduced in 1988, with the A320 variants, which were soon followed by A321 (1994) and A319 (1996) variants (Table 4). Similar to the Boeing family, the Airbus A320 family includes 14 main variants, and these also range in weight from approximately 56 tonnes up to the A321XLR, which is the heaviest of all the B737/A320 aircraft at 101 tonnes. The tyre pressures similarly increased for the Airbus variants, along with the aircraft weight, with the highest tyre pressure being 59% greater than the lowest tyre pressure value.

Table 3. B737 aircraft family.

Variant	Year	Maximum Mass (kg)	Tyre Pressure (kPa)
B737-100	1967	50,349	1082
B737-200	1967	52,617	1089
B737-300	1984	63,503	1386
B737-400	1988	68,266	1276
B737-500	1989	60,781	1338
B737-600	1998	65,771	1282
B737-700	1997	70,307	1358
B737-800	1997	79,242	1407
B737-900	2000	79,242	1407
B737-900ER	2006	85,366	1517
B737 7 MAX	2016	80,512	1406
B737 8 MAX	2016	82,417	1413
B737 9 MAX	2016	88,541	1448
B737 10 MAX	2024	95,000	1686

Notes: Aircraft data from FAARFIELD [22], the B737 10 MAX weight is an estimate based on information provided by Boeing but is not yet finalised.

As stated above, the impact of a particular aircraft on pavement structures depends on the aircraft weight on the main landing gear, the number and spacing between the main gear wheels and the main gear tyre pressure. Despite the significant increase in tyre pressures and aircraft weights, the spacing between the dual main landing gear wheels has not changed significantly as the two aircraft families have developed. For the B737 family, the −100 to −500 variants all have a main gear wheel spacing of 775 mm, whereas the −600 to −900 and MAX variants have a slightly wider spacing of 864 mm. In contrast, every single Airbus A320 variant has the same 927 mm spacing between the main gear wheels. This is wider than all the B737 variants but the A320 variants are generally heavier than the comparable B737 variants, which offsets the greater wheel spacing.

Table 4. A320 aircraft family.

Variant	Year	Maximum Mass (kg)	Tyre Pressure (kPa)
A318-100 STD	2003	56,400	1020
A318-100 OPT	2003	68,400	1241
A319-100 STD	1996	64,400	1193
A319-100 OPT	1996	68,400	1248
A319neo	1996	75,900	1310
A320-200 STD	1988	73,900	1379
A320-200 OPT	1988	78,400	1441
A320neo	1988	70,400	1220
A321-100 STD	1994	83,400	1358
A321-100 OPT	1994	85,400	1393
A321-200 STD	1994	89,400	1462
A321-200 OPT	1994	93,900	1500
A321neo	2017	97,400	1504
A321XLR	2023	101,000	1620

Note: Aircraft data from FAARFIELD [22].

To take the combined effect of tyre pressure, aircraft weight and wheel spacing into account, the ACR of each aircraft was calculated, for a category A (high strength) subgrade and for a category D (ultra-low strength) subgrade (Table 5). In general, the A320 variants have slightly higher ACR values, indicating that the additional weight associated with the Airbus variants has a greater effect than the larger main gear wheel spacing associated with the Airbus aircraft, compared to the Boeing aircraft.

When the aircraft weight and tyre pressure values are considered by the year of aircraft variant introduction, it is clear that the Boeing aircraft were developed in a more incremental manner than the Airbus equivalents (Figure 3). For example, the first Airbus variants were the A320-200 STD, A320-200 OPT and A320neo, which all had a weight of 70–79 tonnes and were introduced in 1998. These are comparable to the B737-400 to -600 variants, which were introduced at about the same time. This probably reflects the desire of Airbus to directly compete with the newest Boeing variants. Airbus then introduced competitors, in the form of the A318 variants in 2003, for the smaller B737-100 and -200, which have been in service since the 1960s.

What is clear is that aircraft from both manufacturers have become more demanding over time, with a significant increase in ACR values (Figure 3). It is also clear that the increase in aircraft weight is enabled by a similar increase in the aircraft tyre pressure (Figure 4). Importantly, all these developments have come with little or no change in their aircraft wheel span, wingspan and height. That means that the heaviest of these aircraft variants can operate into airports with generally the same runway and taxiway width as the smaller variants. That is, all the B737/A320 aircraft variants can operate on a 45 m wide runway and an 18 m wide taxiway. This has enabled an incremental demand on regional airport pavements, as the new and heavier variants have replaced the lighter aircraft variants.

Table 5. Flexible B737/A320 Aircraft Classification Ratings.

Boeing B737 Family			Airbus A320 Family		
Variant	**Subgrade A**	**Subgrade D**	**Variant**	**Subgrade A**	**Subgrade D**
B737-100	212	290	A318-100 STD	225	297
B737-200	241	311	A318-100 OPT	292	376
B737-300	292	389	A319-100 STD	281	364
B737-400	319	447	A319-100 OPT	309	390
B737-500	279	374	A319neo	340	443
B737-600	296	389	A320-200 STD	345	444
B737-700	321	422	A320-200 OPT	368	474
B737-800	377	508	A320neo	316	416
B737-900	382	515	A321-100 STD	399	535
B737-900ER	423	572	A321-100 OPT	412	553
B737-7MAX	389	526	A321-200 STD	437	584
B737-8MAX	399	543	A321-200 OPT	462	621
B737-9MAX	435	601	A321neo	481	651
B737-10MAX	475	660	A321XLR	510	685

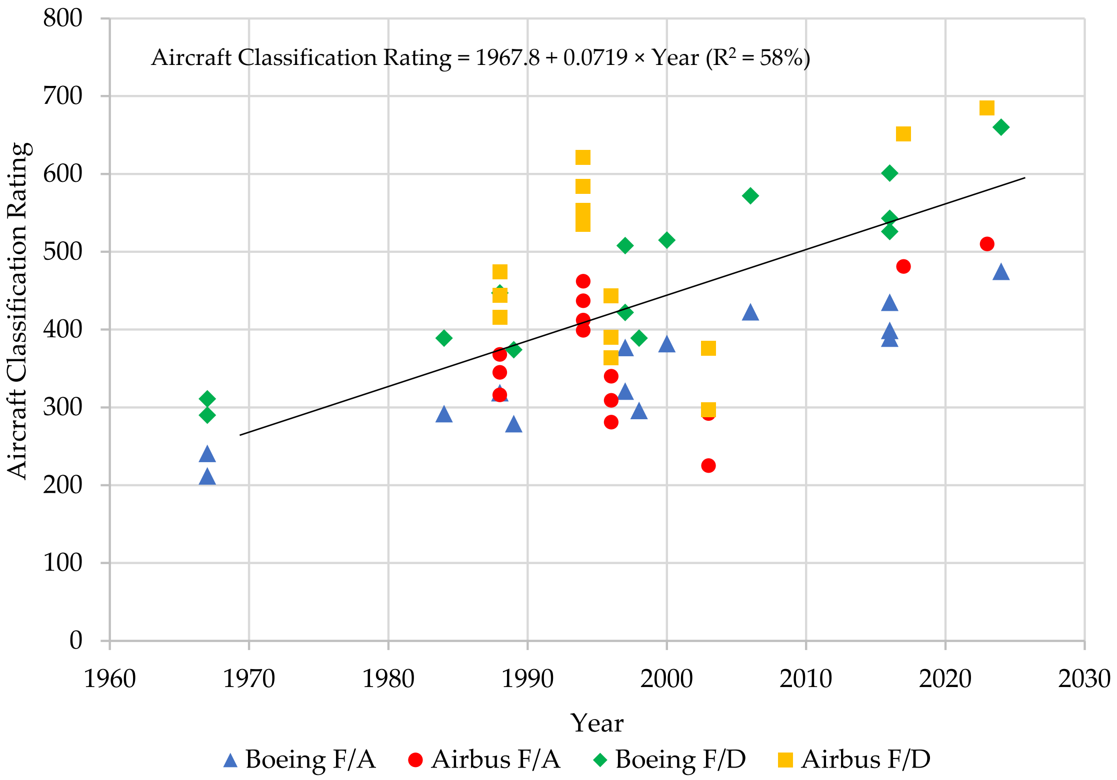


Figure 3. Aircraft Classification Rating by year of aircraft introduction.

4.2. Effect on Pavement Thickness and Life

The evolution of the B737/A320 aircraft variants over time is only important if significant increases in the strength of pavements required to support them are also necessary. For typical thick and thin flexible and rigid pavements, the CDF was calculated for each aircraft variant, recalling that thick and thin were subjectively determined to provide a reasonable range of CDF values, as explained previously. The results are summarised in Figure 5 (flexible pavement) and Figure 6 (rigid pavement).

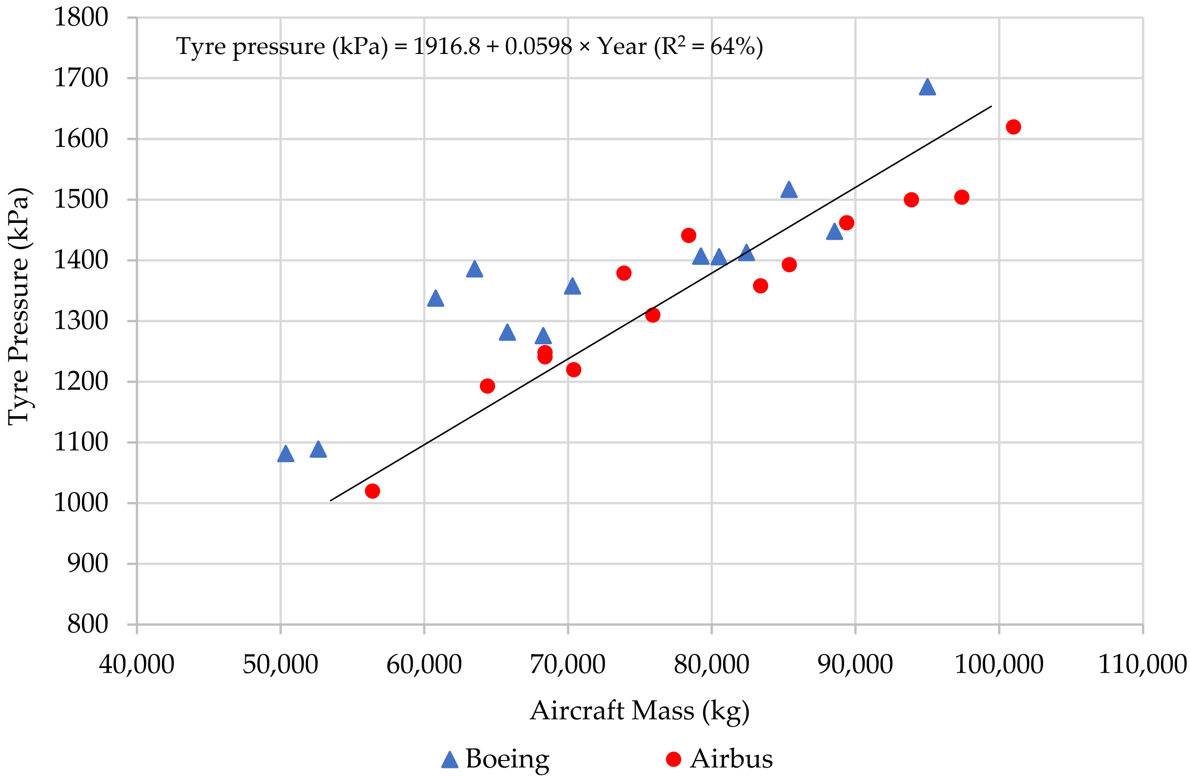


Figure 4. Aircraft tyre pressure increases with aircraft weight increases.

Figure 5 shows the generally greater impact on pavement life due to the Airbus A320 variants, compared to the Boeing B737 variants. This was also reflected in the ACR values (Table 5) but is magnified in the pavement life calculations. That is due to the high sensitivity of pavement life to aircraft weight [1], which results in a more than 800-old (Airbus) and 1300-fold (Boeing) increase in the CDF value, for an average 2.25-fold increase in the ACR value. Similarly, for rigid pavements, the CDF values increased by an average of 52,900-fold, for the same 2.25-fold increase in ACR. By comparing the relative effects on flexible and rigid pavements, it is clear that any evolution of aircraft variants over time will impact rigid pavements more than it does the equivalent flexible pavements. It is also clear that any pavement designed for the A321 XLR or the B737 10 MAX will be insignificantly impacted by the A318, A319, A320 and the B737-100 to B727-800 variants. That is, the smaller variants could be removed from the design aircraft traffic loadings, whenever the newest variants are included, without impacting the resulting pavement strength.

The inverse of pavement life for a fixed pavement thickness is the thickness required for a given pavement life or aircraft load repetitions. The fine crushed rock base thickness, for the typical pavement detailed in Figure 2, is summarised in Figure 7 for both aircraft families and for the four typical subgrade conditions (Table 1). The equivalent rigid pavement thicknesses are summarised in Figure 8.

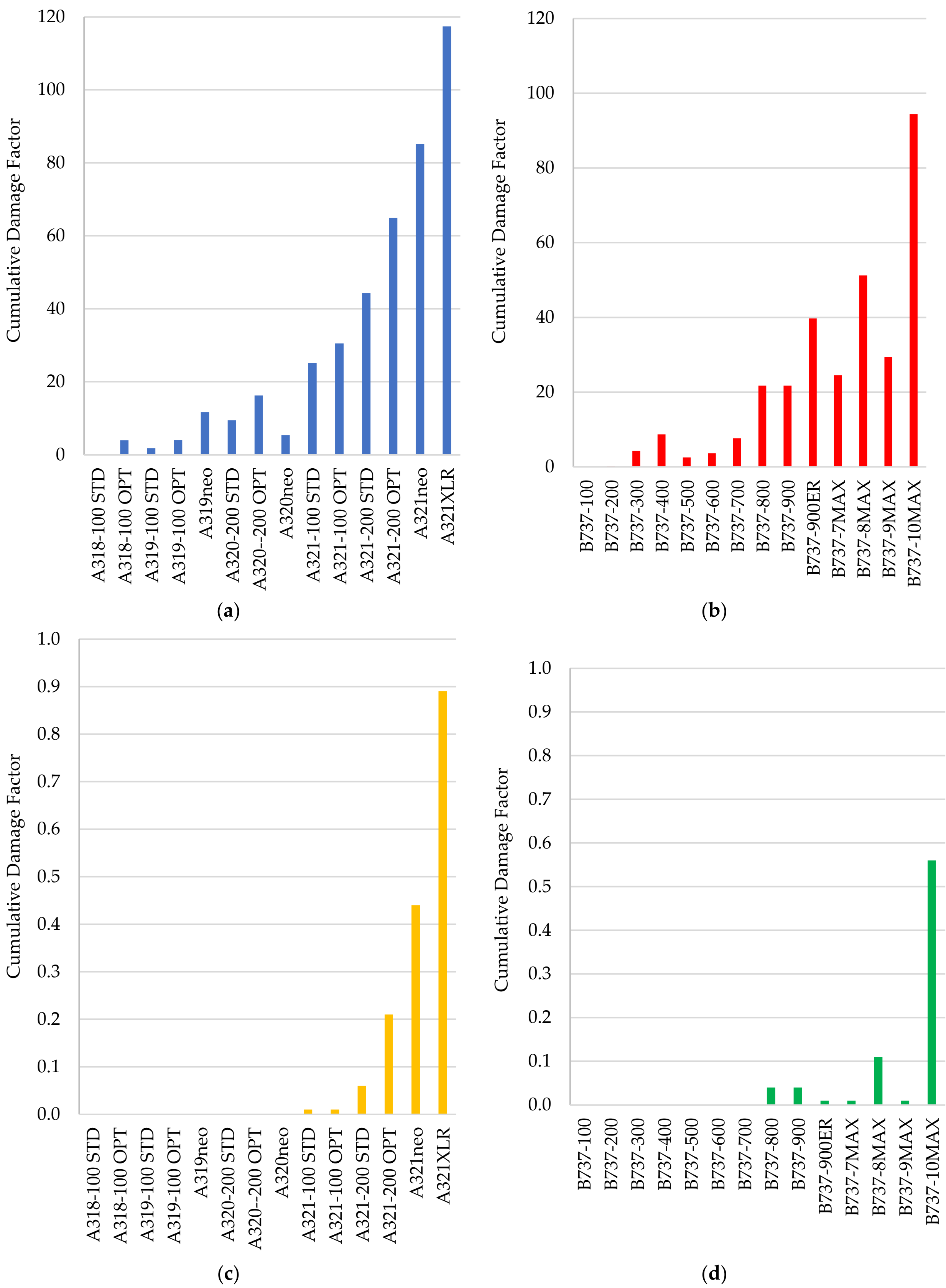


Figure 5. Effect of aircraft variant on fixed flexible pavement thickness for (**a**) A320 on thin pavement, (**b**) B737 on thin pavement, (**c**) A320 on thick pavement and (**d**) B737 on thick pavement.

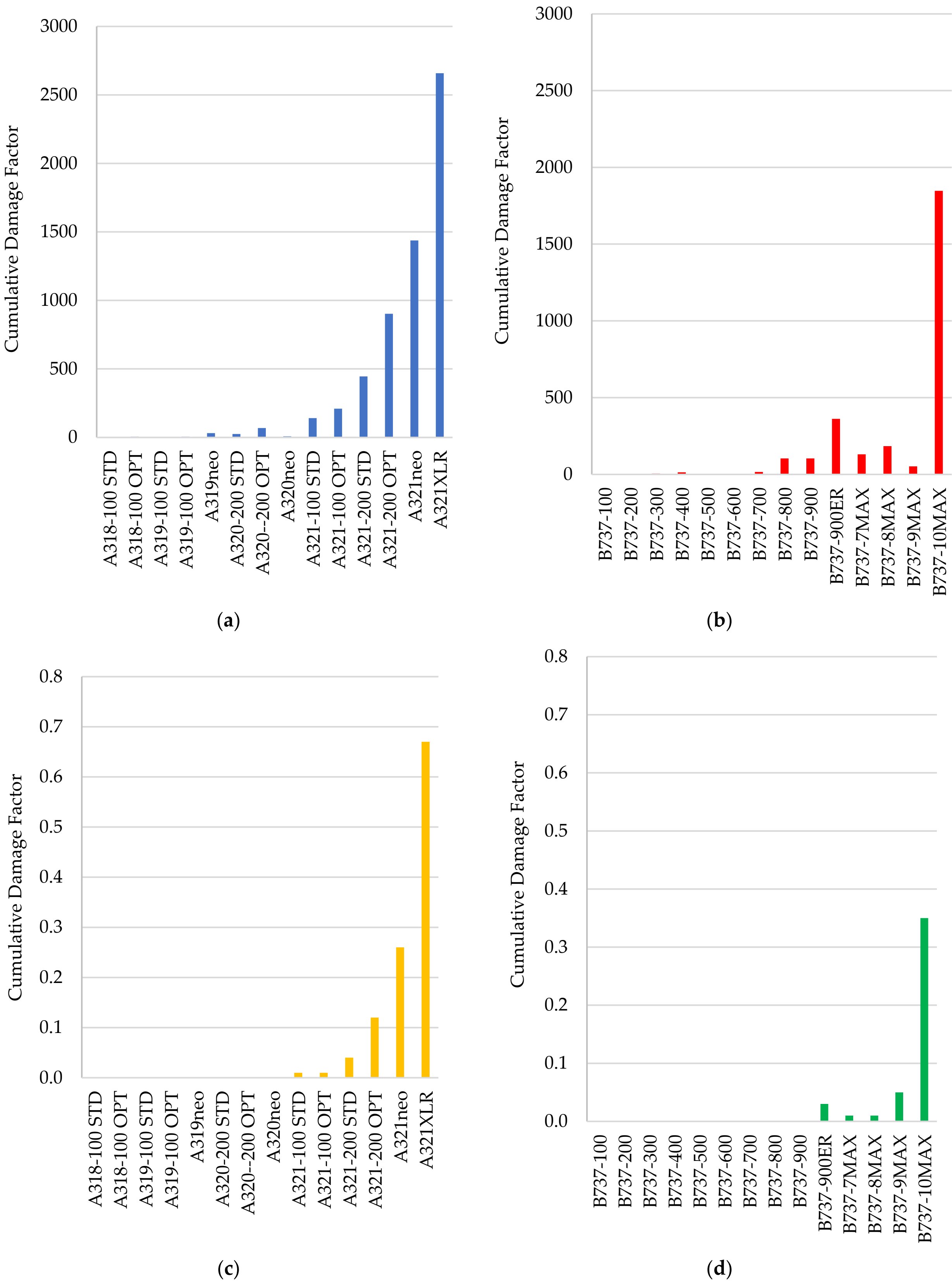


Figure 6. Effect of aircraft variant on fixed rigid pavement thickness for (**a**) A320 on thin pavement, (**b**) B737 on thin pavement, (**c**) A320 on thick pavement and (**d**) B737 on thick pavement.

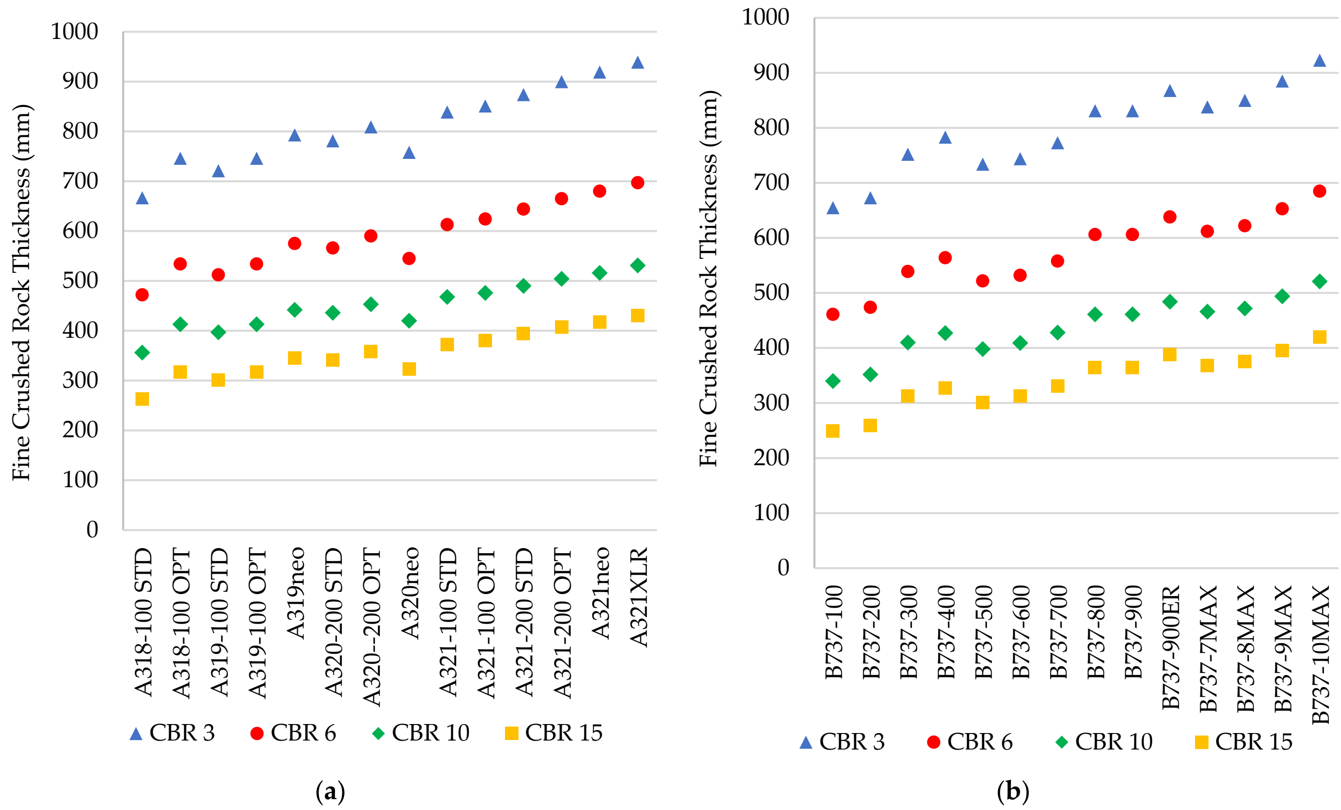


Figure 7. Flexible pavement thicknesses for (**a**) A320 and (**b**) B737 aircraft.

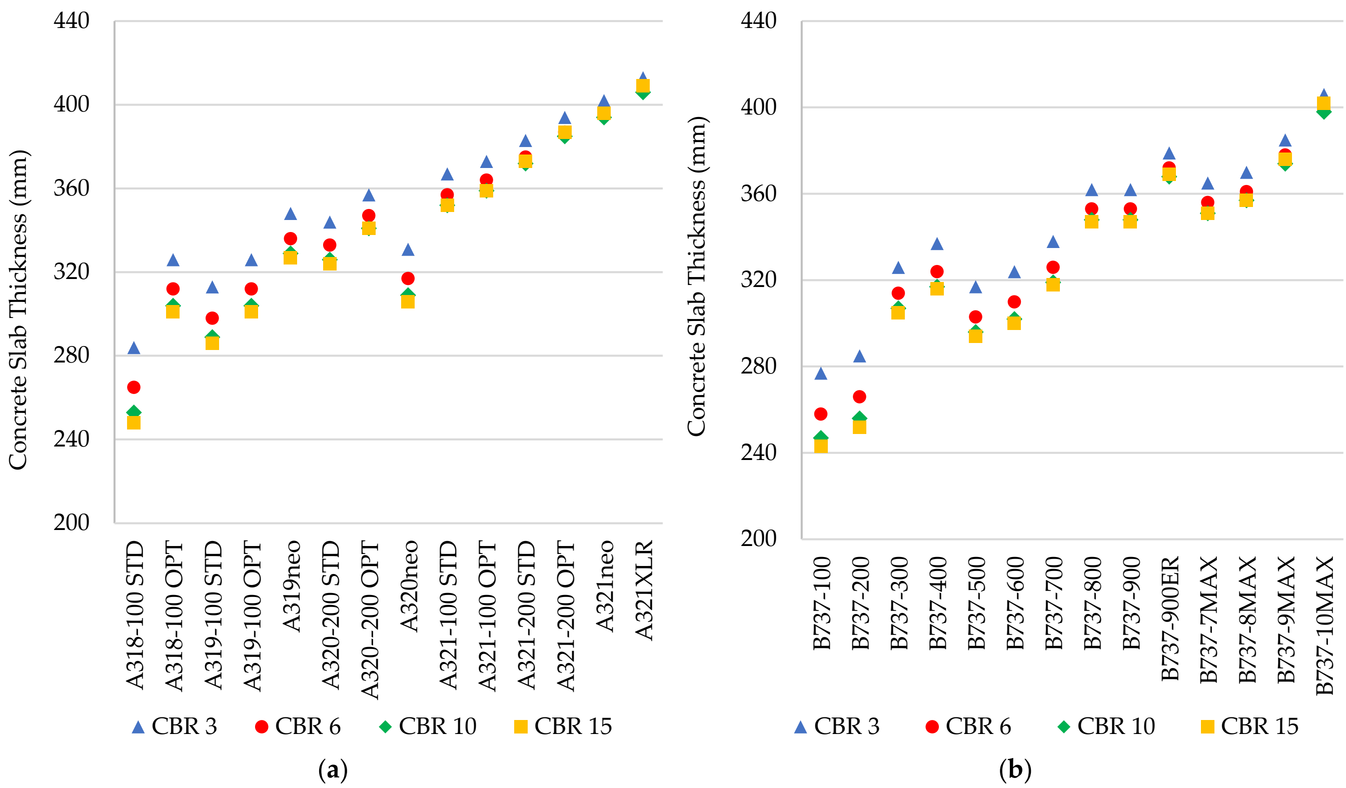


Figure 8. Rigid pavement thicknesses for (**a**) A320 and (**b**) B737 aircraft.

Figure 7 clearly demonstrates the sensitivity of flexible pavement thickness to both subgrade support and aircraft weight. By comparison, the rigid pavement thicknesses are sensitive to aircraft weight but are much less sensitive to subgrade support, indicated by the overlapping of the thicknesses for the different subgrade bearing capacity values. On average, the heaviest variant required a slab thickness (rigid pavement) or a finely crushed rock base thickness (flexible pavement) 51% greater than that required by the lightest variants. Furthermore, despite the significant differences in the ACR values and the CDF values, the pavement thicknesses were similar for the A320 variants and their equivalent Boeing variants. As a result, when the aircraft weight and/or the ACR values are comparable, the Airbus variant can be used as a proxy for both the Airbus and equivalent Boeing variants and vice versa, for the purpose of pavement thickness determination.

4.3. Practical Examples of Effects

The comparison of aircraft variant weights, tyre pressures, ACR values and even pavement thicknesses and structural lives is all theoretical. To demonstrate the practical importance of this issue, real-life case study examples are presented. The four examples that follow are all real and are representative of the various regional airports at which the B737/A320 is the dominant, or at least a significant, aircraft in the traffic loadings. To add context and practical impact to the examples, the cost of the additional pavement thickness and the embodied carbon associated with that additional thickness were also estimated. For these examples, the additional or increased pavement thickness were reported to the nearest 1 mm. Although that is too precise for practical pavement design, that level of precision provided for a more accurate estimation of the impact on the cost and environmental impact associated with the larger aircraft variants.

The embodied carbon and the financial cost of the additional pavement thickness were estimated based on material rates developed by previous similar research (Table 6). In all cases, the embodied carbon and financial costs were all-in rates that represent the supply, production and construction processes. That implies that the maintenance, use and rehabilitation of the various pavements was not significantly different. That reflects the slightly increased pavement thickness associated with the heavier aircraft variants not significantly affecting maintenance requirements, which are dominated by age-related resurfacing of flexible pavements [12] and joint crack/spall repairs for rigid pavements [41].

Table 6. Material embodied carbon and financial cost rates.

Material	FAA Designation [42]	Embodied Carbon ($kg \cdot eCO_2/m^3$)	Financial Cost (AUD/m^3)	Source Reference
Asphalt concrete	P-401	357	1042	[43]
Portland concrete	P-501	325	835	[44]
Crushed rock base	P-209	144	304	[45]
Natural gravel sub-base	P-154	102	208	[45]

Note: All financial costs are Australian dollars in 2023 (AUD).

4.3.1. Example 1

Example 1 was a regional airport that had been upgraded to accommodate Saab 340B, Dash 8-Q400 and occasional B737-400 aircraft (Table 7). However, the B737-400 was subsequently proposed to be replaced by either a B737 8 MAX or an A321XLR. The upgraded flexible pavement structure comprised:

- 100 mm asphalt concrete;
- 400 mm crushed rock base;
- 553 mm uncrushed gravel sub-base;
- Subgrade (CBR 3%).

Table 7. Example 1 aircraft traffic loadings.

Aircraft	Mass (kg)	Annual Departures	Total Departures
Saab 340B	29,347	8000	160,000
Dash8-Q400	13,154	12,000	240,000
B737-400	68,266	1000	20,000

The upgraded pavement was adequate for the design aircraft traffic loadings (Table 7) and the B737-400 dominated the pavement analysis, with a damage factor (DF) of 1.0, which was equal to the CDF over the 20-year design life, even though the annual departures were much lower than for the other (smaller) aircraft. However, when the B737-400 was replaced by the A321XLR in the structural analysis, the CDF increased to 30.6. That indicates that a more conservative assumption, that the A321XLR would be the proxy for all B737/A320 aircraft, suggested that the already upgraded pavement would structurally fail in less than one year.

To increase the strength of the pavement to that required for the A321XLR, two options were considered. The first was an increase in the sub-base layer thickness, which is the lowest-cost material in flexible pavement. An additional 254 mm of P-154 was required. Increasing the sub-base thickness would have been possible at the time of the pavement upgrade but would not be practical as a further upgrade because it requires the asphalt concrete surface and the crushed rock base to first be removed. Therefore, a structural asphalt overlay was also considered. An additional 155 mm of asphalt concrete (P-401) thickness was required for the heavier A321XLR, to replace the B737-400 aircraft loadings.

When extended over the 45 m wide by 1900 m long runway, the additional embodied carbon was more than 2200 tonnes for the thicker natural gravel sub-base, or more than 4500 tonnes for the structural asphalt overlay (Table 8). Similarly, the additional gravel sub-base was estimated to cost AUD 4.7 M, while the structural asphalt overlay was estimated to cost AUD 13.8 M. In light of the existing pavement preventing the sub-base thickness being increased, the embodied carbon and financial cost associated with the structural asphalt overlay were expected to be necessary. Even considering the age of the existing asphalt surface, and assuming it imminently required a 55 mm thick maintenance resurfacing, the remaining additional 100 mm of asphalt required for strengthening was still associated with an additional 3000 tonnes of embodied carbon and AUD 8.9 M, approximately tripling the carbon and cost associated with the maintenance overlay option.

Table 8. Example 1: flexible pavement embodied carbon and financial cost options.

Option	Additional Embodied Carbon (kg·eCO_2)	Additional Financial Cost (AUD)
Existing B737-400 design	Nil	Nil
Additional 254 mm of P-154 sub-base thickness for A321XLR	2,215,134	4,517,143
Additional 155 mm of P-401 asphalt concrete thickness for A321XLR	4,731,143	13,809,105
Additional 100 mm of P-401 asphalt concrete thickness for A321XLR, giving credit for routine maintenance overlay at the same time	3,052,350	8,909,100

4.3.2. Example 2

Example 2 was also a flexible regional airport pavement upgrade. The airport is a tourist destination, and the most frequent aircraft are domestic A320-200 STD and B737-800 aircraft. However, some international A330-300 aircraft were also included in the pavement upgrade design (Table 9). The pavement upgrade was comprised of:

- 80 mm asphalt concrete;
- 250 mm foamed bitumen stabilising granular base;

- Residual existing uncrushed aggregate sub-base;
- Natural CBR 10% subgrade.

Table 9. Example 2: aircraft traffic loadings.

Aircraft	Mass (kg)	Annual Departures	Total Departures
A330-300 STD	230,900	700	14,000
A320-200 STD	73,900	4800	96,000

The upgraded pavement design was dominated by the larger A330-200, which was associated with a CDF of 1.0, rendering the A320-200 insignificant by comparison. Within five years of the upgrade being completed, the main domestic carrier advised of an imminent transition to heavier A321neo or A321XLR aircraft to replace the previous A320-200.

If the A321XLR was permitted to operate at 101 tonnes, the theoretical structural life of the previously upgraded pavement would be reduced to just 3.2 years, implied by a CDF value of 6.2. That is, despite being lighter than the A330, the heavier A321 had become the critical aircraft in the traffic loadings.

Based on a discussion with the airline and taking into account the distance of the proposed flight sectors, it was determined that 85 tonnes was a reasonable maximum weight for the A321 departures. It was subsequently determined that at 101 tonnes, an additional 36 mm of structural asphalt surfacing would be required. When this was reduced to a departing weight of 85 tonnes, the upgraded pavement had a theoretical life of 18.6 years, which is marginally below the 20-year structural design life. Alternatively, the 80 mm thick asphalt surface was required to be increased to just 81 mm, to achieve the 20-year design life. This also resulted in the A330 returning as the critical aircraft. The three options and the estimated carbon and cost of each are summarised in Table 10, extended over the 45 m wide by 2400 m long runway.

Table 10. Example 2: flexible pavement embodied carbon and financial cost options.

Option	Additional Embodied Carbon (kg·eCO_2)	Additional Financial Cost (AUD)
Existing A320-200 STD and A330-200 STD design	Nil	Nil
Replacement of A320-200 STD with maximum weight A321XLR design	1,388,016	4,051,296
Replacement of A320-200 STD with maximum weight A321neo design	925,344	2,700,536
Replacement of A320-200 STD with 85 tonnes design weight A321neo	38,556	112,536

By simply asking the airline what the realistic operating weight of the new aircraft would be, at least 886 tonnes of embodied carbon and at least AUD 2.5 M were saved. However, in practice, 81 mm is the same as 80 mm of asphalt, when construction tolerances are taken into account, meaning that the previously upgraded pavement did not require any additional strength for the A321neo operations, at the realistic 85-tonne departure weight.

4.3.3. Example 3

Example 3 was a remote airport located on an island in the Pacific Ocean. The historical aircraft for pavement thickness determination was the A321-100 STD and the pavements were upgraded for that aircraft at a frequency of 2200 annual departures, at 83,400 kg. The upgraded pavement comprised:

- 100 mm new asphalt concrete surface;
- 150 mm existing base course asphalt concrete;
- 444 mm crushed rock base course;
- Subgrade CBR 6%.

During the mobilisation phase of the project, the dominant airline advised that the A321-100 STD would be imminently replaced by the A321XLR. The frequency of departures was not expected to change. The theoretical effect on the pavement was to reduce the structural life from 20 years to less than 1.5 years, based on a CDF of 14.6. However, the runway was unable to be lengthened and the existing runway length would not allow maximum weight A321XLR operations. Following a discussion with the airline, it was determined that a variable aircraft weight would be planned, depending on the prevailing weather conditions and the subsequent effect on the required runway length. To understand the impact of the variable A321XLR weight on the pavement, the thickness of base course asphalt below the 100 mm thick surface was calculated for various aircraft weights from 80 tonnes to 95 tonnes. The additional thickness required, above that for the A321-100 STD, ranged from −13 mm (80 tonnes) to 66 mm (101 tonnes), as shown in Figure 9.

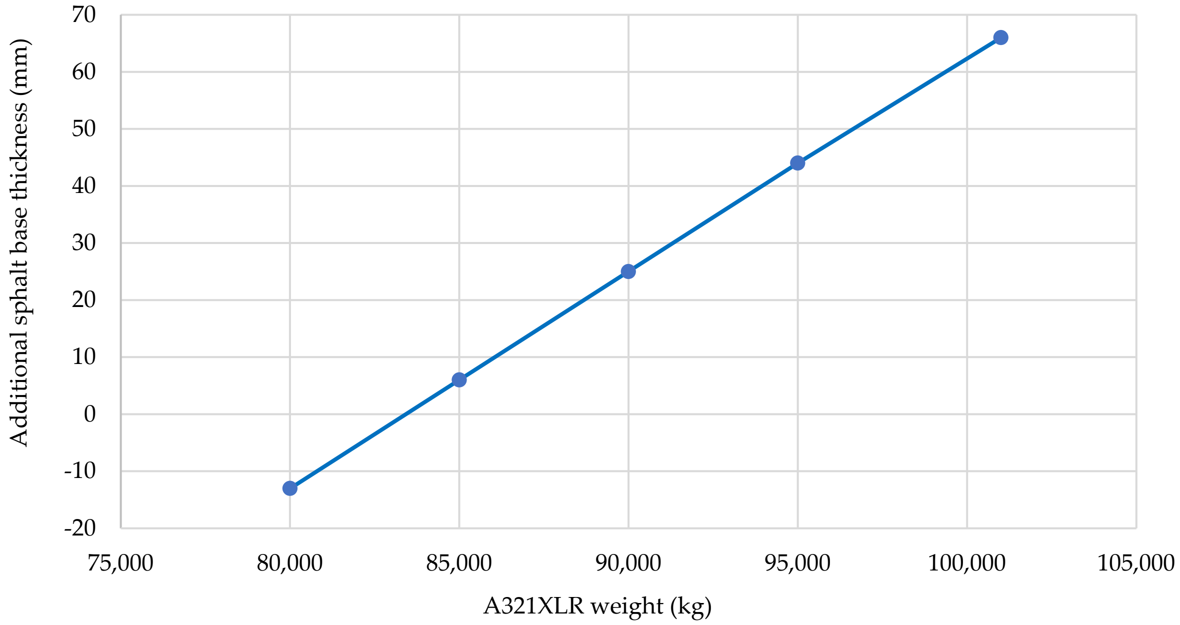


Figure 9. Additional asphalt thickness as a function of A321XLR operating weight.

It is clear that as the aircraft weight increased beyond that practically limited by the runway length, the required structural asphalt thickness increased significantly. That increased thickness had a significant impact on the embodied carbon and financial cost of the upgrade works, when extended over the 2000 m long and 45 m wide runway (Figure 10). Because the A321XLR weight was limited to the practical weight allowed for the fixed existing runway strength, it was estimated that 190 tonnes to 2120 tonnes of embodied carbon and AUD 0.5 M to AUD 6.2 M were saved in structural asphalt thickness. However, the operational capability was not impacted because the runway length would likely limit the practical A321XLR weight to 85 tonnes, regardless of the upgraded runway strength.

Example 3 also included new rigid pavement aircraft parking pads for two aircraft. The dimensions of each pad were 30 m (wide) by 35 m (long). The initially determined pavement for the A321-100 STD was:

- 378 mm of 4.5 MPa flexural strength concrete;
- 15 mm lean mix concrete;
- CBR 6 subgrade.

However, when the A321XLR at 101 tonnes was considered in place of the A321-100 STD, the CDF increased to 49.0, indicating a theoretical structural life of less than six months. To accommodate the A321XLR at 101 tonnes, the pavement slab thickness would need to be increased by 51 mm to 429 mm. When the A321XLR operating weight was reduced to reflect the runway length limitation, the required concrete slab thickness ranged from 366 mm (80 tonnes) to 412 mm (95 tonnes).

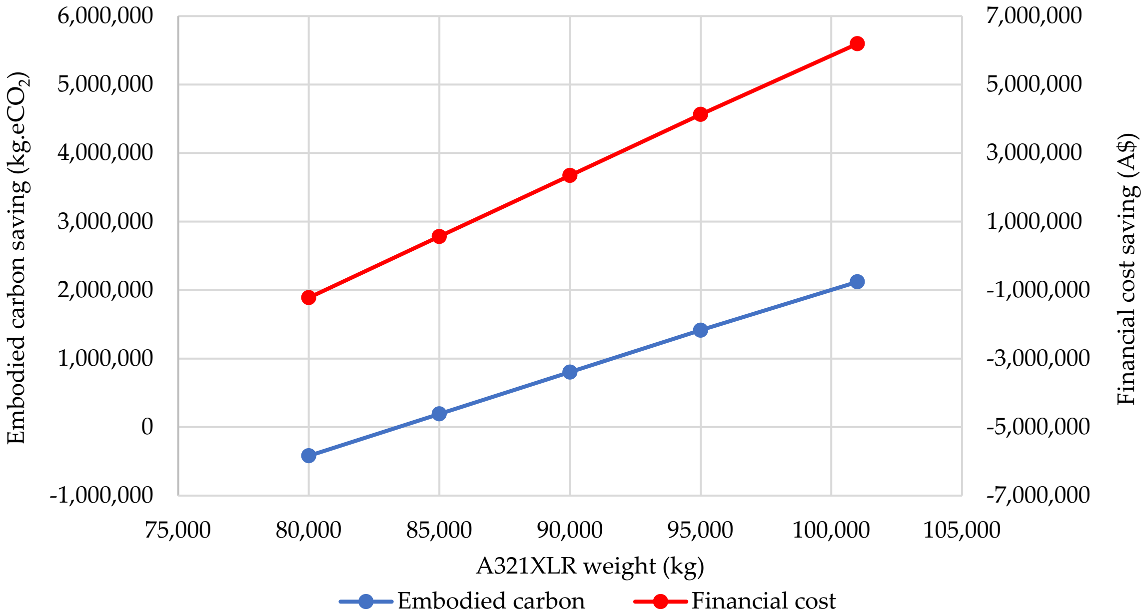


Figure 10. Additional embodied carbon and financial cost of heavy A312XLR aircraft.

When extended over the 2100 m^2 of the two concrete pads, the excess embodied carbon and financial cost were:

- −8190 kg·eCO_2 (80 tonnes) to 34,808 kg·eCO_2 (101 tonnes) of embodied carbon;
- −AUD 21,042 (80 tonnes) to 89,429 (101 tonnes) in financial cost.

4.3.4. Example 4

Example 4 was a large regional airport that included significant civilian and military aircraft operations. The existing flexible pavement was required to be resurfaced and the existing rigid pavements required reconstruction. The flexible runway pavement was 2500 m long and 45 m wide, while the irregularly shaped rigid pavement runway ends and taxiways were 18,000 m^2 in area. The design of aircraft traffic loadings included many common military and civilian aircraft types (Table 11). The A321XLR was adopted as a proxy for all A321 and B737 MAX aircraft, at the maximum 101 tonnes. The existing flexible runway pavement comprised:

- 80 mm asphalt concrete;
- 400 mm crushed rock base;
- 425 mm uncrushed gravel sub-base;
- Natural subgrade CBR 6%.

The initial assumption that all A321/B737 MAX aircraft would be represented by the 101 tonne A321XLR indicated a need to increase the asphalt surface thickness from 80 mm to 152 mm. With a DF of 0.94, the A321XLR dominated this requirement, despite the inclusion of significantly larger aircraft in the traffic loadings, such as the C-17A (265 tonnes), C-5 (348 tonnes) and A330 (233 tonnes). Furthermore, because the existing asphalt surface exhibited significant top-down cracking associated with acid modified binder [46] the existing surface was also nominated to be removed and replaced. The result was the transformation of routine asphalt resurfacing into a significantly more disruptive and more expensive rehabilitation and strengthening. This was despite no actual significant change in the aircraft traffic loadings, and no structural deficiency being visually identified in the existing pavement.

Table 11. Example 4: aircraft traffic loadings.

Aircraft	Mass (kg)	Annual Departures	Total Departures
C-17A	265,351	176	3520
C-5	348,812	17	340
B757-200	122,900	11	220
C-130	74,400	152	3040
B737	85,800	150	3000
A330	233,000	100	2000
B767-300	188,240	47	940
B737-800	77,790	10	1200
B707-300	160,000	60	1000
CS100	70,000	9125	182,500
A320-20std	78,400	2190	43,800
A321XLR	*101,000*	*9316*	*186,320*
B737-800ER	79,242	10,950	219,000

Note: italics indicates the A321XLR representing all A321 and B737 MAX aircraft.

The reasonableness of the A321XLR loading was questioned. The airline advised that for an aircraft full of passengers and freight, on a significant domestic Australian commercial flight sector (3150 km), the maximum departure weight of the A321XLR would not exceed 90 tonnes. For the significantly shorter proposed sectors (1680 km to 2540 km), a maximum departure mass of 83.4 tonnes, which is equal to that of the A321-100 STD aircraft, was a more reasonable assumption.

When the existing pavement structure was evaluated for the same design traffic loadings but with the A321XLR aircraft weight reduced to 83.4 tonnes, the existing pavement was adequate for the 20-year design life. Furthermore, the A321XLR was no longer the single dominant aircraft, with a DF of 0.27, with a CDF value of 0.94. This allowed the existing surface to be removed and replaced without any structural improvement. This saved 8100 tonnes of asphalt, which meant a reduction in the embodied carbon of 2850 tonnes of eCO_2, and a reduction in the financial cost of AUD 8.3 M.

For the rigid pavement reconstruction, the required concrete slab thickness was 438 mm when the A321XLR was included at 101 tonnes, over a foundation of 200 mm of crushed rock (P-209) sub-base, over the existing CBR 6% subgrade. However, when the A321XLR weight was reduced to 83.4 tonnes, the concrete slab thickness was reduced to 396 mm. That is a 42 mm reduction in concrete thickness. At 101 tonnes, the A321XLR almost completely dominated the design, with a DF of 0.99, which reduced to 0.52 at the more reasonable 83.4 tonnes. The 42 mm slab thickness reduction was associated with 1535 tonnes of eCO_2 and AUD 3.9 M.

4.3.5. Relative Embodied Carbon and Financial Cost Reductions

The minimum embodied carbon and financial cost reductions associated with more reasonable B737/A320 aircraft traffic loading assumptions were each converted to a saving per pavement area for each of the four examples. The embodied carbon relative saving was 2.1–85.3 $kg{\cdot}eCO_2/m^2$ and the financial cost saving was AUD 6–219/m^2 (Figure 11). In every case, the additional pavement strength associated with the maximum weight A321 assumption in design was not required and providing it would be unreasonable, meaning the alternate approach did not introduce any practical risk or limitation on airport operations. The magnitude of the embodied carbon and financial cost reductions depended on the specific project circumstances but were significant for any airport that desires to be more sustainable and economically responsible.

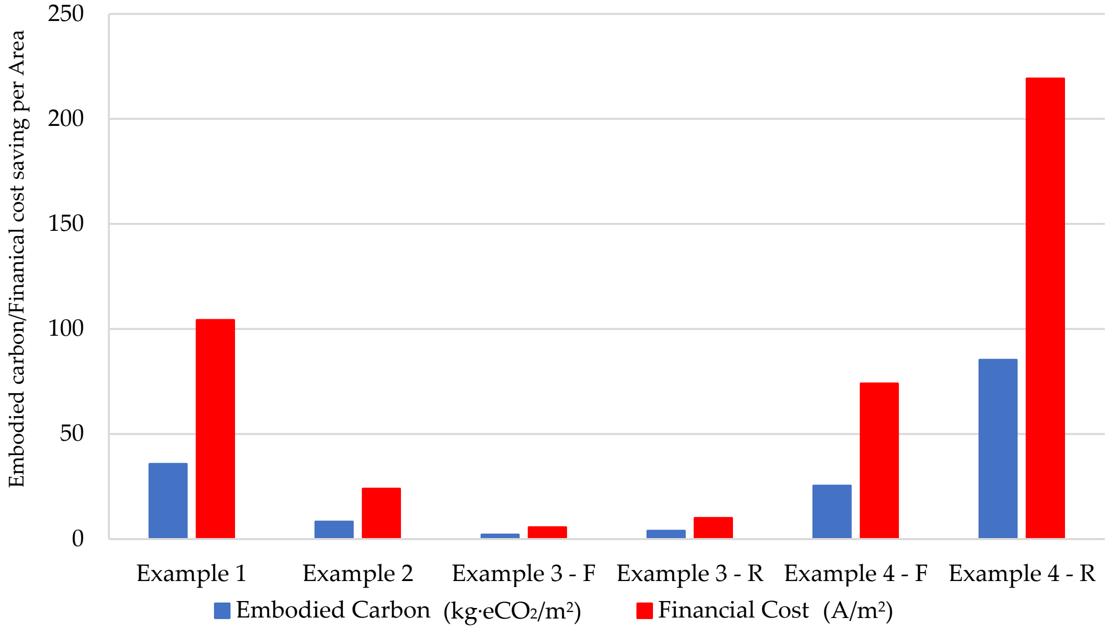


Figure 11. Relative embodied carbon and financial cost savings. Note: R and F indicate the flexible and rigid pavements where both pavement types were considered for the sample example airport.

Researchers may also use or adapt the methods used in this research to provide quantified financial costs and embodied carbon values associated with other pavement designs. By placing their research into a practical context for practitioners and decision-makers, researchers are expected to attract more interest in their work and greater acceptance of their findings.

5. Conclusions

The A320 and the B737 families of narrow-body commercial jet aircraft are examples of aircraft families that have evolved over many years, resulting in incrementally heavier aircraft on commensurately high tyre pressures, placing more demand on the pavements on which they operate. Through theoretical pavement life and pavement thickness calculations, as well as real-life pavement upgrade examples, the importance of understanding the practical maximum operating weight of the potentially heavier aircraft is clear. For example, within the context of the pavements considered, the heaviest variants required on average a 51% thicker pavement base than the lightest variants. Furthermore, based on four regional airport examples from Australia, it was found that the additional embodied carbon associated with these new aircraft variants was 2.1–85.3 kg·eCO_2/m^2 of pavement, while the additional financial cost was AUD 6–219/m^2 of pavement. It is critical that airport pavement thickness designers challenge the weight of design aircraft and do not take the simple and conservative approach of adopting the maximum weight of the heaviest variant within each aircraft family. By doing so, significant additional pavement thickness will be constructed for no practical benefit, creating an environmental (embodied carbon) and economic (financial cost) burden. In the future, this analysis should be extended to include other airport pavement types, such as hybrid or composite pavements, and pavements containing significant stabilised base layers.

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