# LIGHTWEIGHTING OF DOUBLE-DECKER BUSES

by

**Christopher Micallef**

CEng ¦ MIMechE ¦ AFHEA ¦ MSc ¦ B.Eng (Hons)

INNOVATION REPORT

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# ABSTRACT

The bus industry is currently undergoing extensive transformation as cities around the world push for the rapid introduction of electric buses. Lightweighting of bus structures is identified by leading experts as one of the key technologies necessary to enable and assist this revolution in the industry. Alexander Dennis Ltd. (ADL) is the UK's largest bus manufacturer and a worldwide leader in the construction of double-decker buses. ADL consider lightweighting to be one of the three main technological pillars of the company and have thus supported various ongoing research programmes with this EngD research programme funded in collaboration with WMG, University of Warwick.

This thesis summarises the outcomes of the EngD programme, the primary objective revolving around the identification of innovative yet feasible lightweighting opportunities applicable to ADL double-decker buses. A systematic review of the state-of-the-art of bus lightweighting followed by a critical analysis of ADL bus structures led to initial feasibility studies of various lightweighting opportunities which in turn led to a lightweighting proposal. An innovative lightweight upper-deck structure design was conceived, developed and proposed to ADL. The holistic redesign of the system achieved a 42% weight reduction whilst also significantly lowering the bus centre of gravity hence enabling further lightweighting of other primary structures. The redesigned upper-deck structures necessitates the novel introduction into the bus industry of two key technologies necessary for its realisation; braided fibre reinforced polymer beam structures and coated polycarbonate glazing.

A study on the feasibility of utilising fibre reinforced composites to manufacture cost-effective curved structural beams was carried out. A state-of-the-art review identified a composite manufacturing process consisting of a bladder-assisted consolidation of braided commingled thermoplastic preforms as ideally suited for the bus industry. Tooling was designed and machined to allow demonstrator beams to be manufactured using the proposed method. A finite-element methodology, that would enable the design of these composite beam structures, was proposed and verified though correlation of simulation performance data with data collected from three point bend tests carried out on test beam structures. Design guidelines including considerations of manufacturing volumes and costs were prepared for use by ADL.

Investigations on the feasibility of polycarbonate glazing application within the bus industry identified gaps in the knowledge of lifetime performance of polycarbonate glazing exposed to bus industry specific conditions. A novel testing set-up was designed to assess the performance of commercially available coated polycarbonate glazing exposed to a harsh daily bus washing environments. Following the successful identification of a suitable coating system, a demonstrator manufacture programme was set-up. This led to the successful manufacture and planned installation on in-service buses of polycarbonate glazing panels achieving 57% component weight reduction when compared to the current laminated-glass glazing panel.

# DECLARATIONS

This innovation report is being submitted to the University of Warwick in support of my application for the degree of Doctor of Engineering (International). Except where acknowledged, all the work is my own. The report has been composed by myself and has not been submitted in any previous application for any other degree.

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# TABLE OF CONTENTS

# LIST OF FIGURES

# LIST OF TABLES

# ABBREVIATIONS

| | |
|---|---|
| **2D** | 2 dimensional |
| **3D** | 3 dimensional |
| **A/C** | Air-conditioning |
| **ADL** | Alexander Dennis Ltd. |
| **AHSS** | Advanced high strength steels |
| **BARTM** | Bladder assisted resin transfer moulding |
| **BEB** | Battery electric bus |
| **BEV** | Full battery electric vehicles |
| **CAD** | Computer aided design |
| **CAE** | Computer aided engineering |
| **CAGR** | Compounded annual growth rate |
| **CCTV** | Closed-circuit television |
| **CF** | Carbon fibres |
| **CFRP** | Carbon fibre reinforced plastics |
| **CLEPA** | European association of automotive suppliers |
| **CNC** | Computer numerical control |
| **COG** | Centre of gravity |
| **CVD** | Chemical vapour deposition |
| **DB** | Diesel bus |
| **DD Bus** | Double-decker bus |
| **E** | Elastic modulus |
| **EngD** | Doctor of Engineering (International) |
| **EV** | Electric vehicle |
| **FCEB** | Fuel cell electric bus |
| **FCH** | Fuel cell hybrid |
| **FE** | Finite element |
| **FR** | Fibre reinforced |
| **FRP** | Fibre reinforced polymer |
| **FTA** | Federal Transit Administration |
| **G** | Shear modulus |

| | |
|---|---|
| **GF** | Glass fibre/s |
| **GFR** | Glass fibre reinforced |
| **GHG** | Greenhouse gases |
| **GVW** | Gross vehicle weight |
| **HEB** | Hybrid electric bus |
| **HGV** | Heavy good vehicle |
| **HP-RTM** | high-pressure resin transfer process |
| **HS CF** | High-Strength Carbon Fibre |
| **HSS** | High strength steel |
| **ICE** | Internal combustion engine |
| **IGPG** | Informal Group on Plastic Glazing |
| **LP-RTM** | Low-pressure resin transfer moulding |
| **MLTB cycle** | Millbrook London transport bus cycle |
| **NDA** | Non-disclosure agreement |
| **NVH** | Noise, vibration and harshness |
| **OD** | Outside diameter |
| **PA** | Polyamide |
| **PAR** | Parallel hybrid electric drivetrain |
| **PC** | Polycarbonate |
| **PECVD** | Plasma enhanced chemical vapour deposition |
| **PMMA** | Poly(methyl methacrylate) |
| **PUR** | Polyurethane |
| **RTM** | Resin transfer moulding |
| **SD Bus** | Single-deck bus |
| **SER** | Serial hybrid electric drivetrain |
| **SS** | Stainless steel |
| **STP** | Silane-terminated-polymer |
| **Takt** | average time between the start of production of one unit and the start of production of the next unit |
| **TFL** | Transport for London |
| **TMR** | Transparency Market Research |
| **TTW GHG** | Tank-to-wheel (local) GHG emissions |
| **ULW** | Unladen weight |
| **US** | United States of America |
| **UV** | Ultra violet radiation |
| **WTT GHG** | Well-to-tank GHG emissions |
| **WTW GHG** | Well-to-wheel GHG emissions |
| **$\nu$** | Poisson’s ratio |

# 1

# INTRODUCTION AND BACKGROUND TO THE RESEARCH

The purpose of this report is to summarise the key findings of a four-year research programme intended to develop lightweight opportunities for bus industry application. The research was carried out as part of a Doctor of Engineering degree (EngD) at the University of Warwick sponsored by Alexander Dennis Ltd.

## 1.1 Motivation for the research

An effective lightweighting project is one where the total mass of a system is reduced whilst still maintaining all the required performance, functionality and characteristics of the system. The direct benefit associated with the weight [#] reduction of a system is a reduction in the energy required to accelerate/decelerate that system. However, the main motivation for any lightweighting project could vary depending on the nature of the system and the benefit that results from the associated reduction in energy conversion.

Within the bus industry, the main drivers for lightweighting are the necessary reduction of both the lifetime operational financial costs and environmental impact. These are also the motivations for this research project. Vehicle mass has a direct and significant effect on the energy required to operate conventional fuel vehicles and hence, a lighter bus translates to better fuel efficiency. The bus market is currently experiencing a revolution, with local governments around the world legislating for zero tail-pipe emission buses. As

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[#] The terms weight and mass are being used interchangeably here and throughout the thesis. Technically, mass, as measured in kilograms is being referenced, however the terms lightweighting and weigh reduction are widely used within the industry and hence the adaptation of the terms herein.

a result, bus manufacturers are rapidly shifting towards the electrification of bus drivetrains [1]. However, conventional fuel has about 100 times the energy density of the current average lithium-ion battery which translates to a bus carrying 3000 kg of lithium ion batteries compared to 250 kg of diesel in order to have enough autonomous range for a one day operation [2]. In addition to this step increase in bus weight brought about by drivetrain electrification, and similar to the trend within the automotive industry, the weight of buses has steadily increased over recent years due to higher specification of passenger safety, comfort and services, additional on-board systems and an increase in height and width of the vehicles. However, the legally imposed gross vehicle weight limits have remained constant and hence the increase in bus weight equates to a reduction in payload capacity. Therefore, a further driver behind lightweighting is that of being able to maintain maximum passenger carrying capacity.

## 1.2 Research aim and objectives

The broad aim of this doctorate research project was to identify lightweighting opportunities which could be applicable to buses manufactured by the UK's largest bus manufacturer, Alexander Dennis Ltd. ADL consistently supplies more than 50% of the UK’s bus demand with its two main models illustrated in Figure 1.1. Its buses operate across numerous territories around the world with the double-decker (DD) bus concept being successfully exported from the UK to the USA, Canada, Mexico, New Zealand, Hong Kong, Malaysia and Switzerland [2].

Figure 1.1: ADL’s E200 and E400 are the best-selling bus models within the UK market, reproduced from [2].

The family of buses that ADL currently offer to the market are considered the state-of-the-art in lightweight bus architecture as will be detailed in chapter 2. ADL's strategy of effective lightweighting through compounded downsizing was one of the key elements behind its very successful product line-up. The company considers lightweighting as one of the three core technologies that it must continue to excel at in order to retain and increase its market share.

As an additional research initiative, in 2014, the company's Engineering Director invested in an EngD research programme whose scope was to identify additional innovative lightweighting opportunities which were currently not being investigated within the company and subsequently aid with the development of proposed solutions. ADL’s approach allowed complete freedom to the direction of research with the main boundary set being the necessity of considering 'real-world' factors. Any proposed lightweighting projects had to take into consideration cost, manufacturability, maintenance, reparability and the operational requirements of ADL buses which would be manufactured across multiple build sites and operated across the world.

## 1.3 Overview of research and the EngD portfolio

The EngD programme required the presentation of a portfolio which consists of three main components, namely the *Submissions*, an *Innovation Report* and the *Personal Profile*.

During this four-year research programme, seven reports detailing separate work packages referred to as submissions were produced. An overview of the progression of this research and the main work packages carried out is presented in Figure 1.2. Additionally the figure illustrates in which submissions the details of the various work packages are presented.

This innovation report presents a summary of the submissions and critical review of the research and development work that led to the innovations produced during the tenure of this EngD. Finally, the personal profile report details how key competencies as defined by the Association of Engineering Doctorates [3] were developed or enhanced throughout this doctoral research programme.

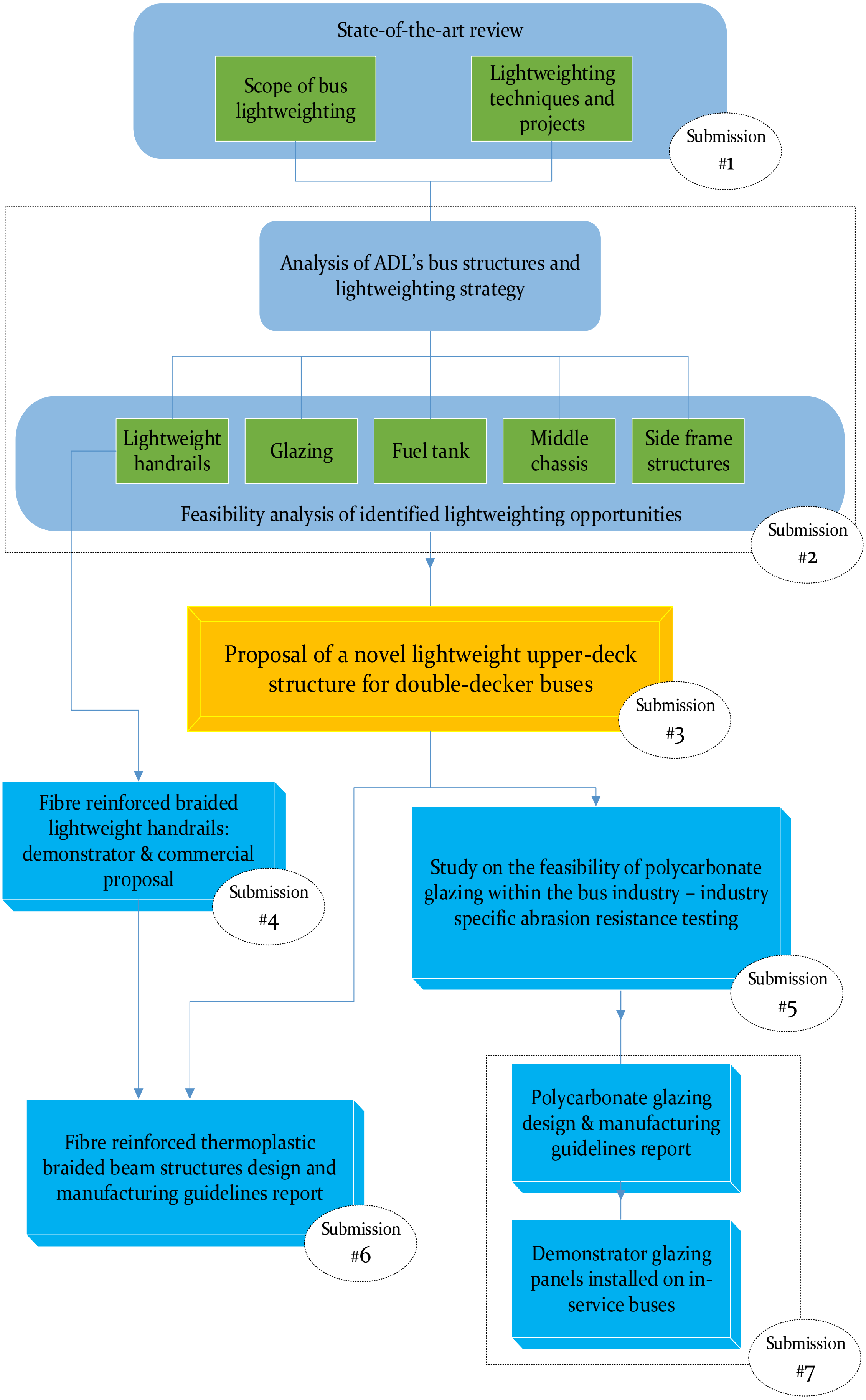


Figure 1.2: Overview of the research and the EngD portfolio submissions.

The following is a summary of the contents of each submission:

***Submission #1*:** Initially, a comprehensive state-of-the-art review of lightweighting technologies in the bus industry was carried out. This review was extended to include technologies currently being employed within other industries such as the rail and automotive industries which could possibly be carried over to the bus industry.

***Submission #2*:** The second phase of the research consisted of a detailed study of the structure of ADL buses as well as collecting information on ongoing lightweighting projects. This information was cross-compared with the state-of-the-art review in order to develop an initial list of possible lightweighting opportunities. A systematic review of the identified lightweighting opportunities was performed and initial feasibility studies were carried out in order to identify lightweighting projects with the most potential and impact whilst being achievable within the project timescale and resources. These initial investigations were carried out with prospective industrial partners in order to assess the realistic feasibility of the projects being assessed. Additionally, various industry-specific exhibitions, seminars and conferences were attended to ensure that the proposed projects were relevant, innovative and feasible.

***Submission #3*:** The state-of-the-art review, critical review of ADL's bus structures and various feasibility studies carried out culminated in the identification and proposal to ADL of an innovative lightweight redesign of the upper-deck structure of DD buses. The proposed concept was novel to the company. The holistic system redesign approach offers various additional benefits besides significant lightweighting potential. Following ADL's acceptance of the project, further detailed design on the concept was carried out as well as a project benefit and risk analysis in order to identify the key risks that needed to be addressed. This led to two separate areas of research which were pursued; lightweight polycarbonate glazing and composite fibre reinforced beam structures.

***Submission #4*:** A feasibility study on the utilisation of composite braided fibre reinforced (FR) tubes as lightweight handrails was executed. Strength verification testing was performed and demonstrator handrail components were successfully manufactured.

***Submission #5*:** A study was carried out to investigate the feasibility of utilising polycarbonate glazing within the bus industry. Testing on the abrasion resistance of potential glazing systems exposed to daily bus washes was executed and, following the identification of a coated polycarbonate glazing system meeting the in-service performance requirements, fire performance testing as well as adhesive compatibility testing was commissioned.

**Submission #6:** The technology evaluated in submission #4 to produce the lightweight handrail systems was further investigated to assess the feasibility of utilising this technology to manufacture the curved structural beams required to realise the proposed upper-deck structure. Manufacturability and cost aspects were evaluated and a computer aided design (CAD) methodology was developed and verified.

**Submission #7:** Following the results of the investigation on the suitability of polycarbonate glazing for utilisation on bus detailed in submission #5, a programme to develop and manufacture demonstrator glazing panels which would be installed for trial on in-service buses was set-up. This collaborative programme included investment by four different companies and additional funding secured from HMV Catapult, UK. Demonstrator panels were successfully manufactured and installation on in-service buses for further in-service performance verification by ADL is underway at time of writing.

This research to identify lightweighting opportunities for buses spanned into various engineering disciplines. Figure 1.3 presents an overview of main topics which were covered throughout this EngD programme by providing a visual depiction of a statistical frequency analysis of the word content of the submissions and this report. The size of the font of each word indicates the frequency of occurrence of the word within the reports.

Figure 1.3: A review of the major themes investigated during this research programme. The two main themes 'lightweighting' and 'structure' have been removed to aid with the graphical representation of the diagram.

## 1.4 Summary of Innovation and Impact

The research *'Lightweighting of double-decker buses'* has resulted in the following principal innovations.

### 1. Proposal of a novel lightweight upper-deck structure for DD buses

A redesigned upper-deck structure achieving a 42% weight reduction of the current structure was conceived, designed and proposed to ADL. The resultant absolute weight saving of 260 kg is equivalent to an increased capacity of four passengers. In addition, given the critical location of the structure, the implementation of this redesign would enable further step-change lightweighting of other structures and system of a DD bus. The proposal benefits from having relatively low technical risk and low capital investment requirements enabling the possibility of a phased introduction to market.

### 2. Application of braided FR composite beam structures within the bus industry

A low-cost manufacturing technique applicable for the production of low-volume thermoplastic braided FR composite beam structures was successfully demonstrated. A simplified methodology for CAD modelling of these beams was developed and verified.

### 3. Abrasion testing of coated polycarbonate glazing panels exposed to specific bus operation conditions

A testing set-up which enabled real-condition exposure of prospective glazing test panels to industry-specific abrasion conditions was developed. Repeatable, robust and "in-service condition" exposure testing was successfully carried out and a suitable commercially available coated polycarbonate glazing system was identified.

### 4. Lightweight polycarbonate glazing panel demonstrators installed on UK buses

A case study on the replacement of complex shaped glass glazing with polycarbonate glazing within the bus industry was carried out. In collaboration with a European market leader, demonstrator panels were successfully manufactured and installed on buses for in-service trials. Besides providing a platform for in-service technology verification, the demonstrator panels achieved 57% lightweighting at a net-lifetime cost benefit on their own right.

## 1.5 Structure of this Innovation Report

This *Innovation Report* is organised in seven chapters.

Chapter 1 presents the motivation behind this EngD research project. A summary of the main innovation outcomes of this research was presented as well as an overview of the research, design and testing which was carried out.

Chapter 2 critically reviews the current state-of-the-art in bus lightweighting technology. This is divided in two main sections. Firstly, the scope and benefit of lightweighting are explored hence defining quantifiable benefits against which prospective lightweighting projects could be measured to assess their feasibility. Secondly, technologies which could deliver real-world feasible lightweighting within the bus industry are reviewed.

Chapter 3 contains two main parts. Firstly, a review of the structure of ADL buses and lightweighting status is presented. Secondly, a review of the various lightweighting opportunity feasibility studies carried out is presented.

Chapter 4 details the proposed lightweight upper-deck structure together with the design philosophy and methodology that was used. The chapter is concluded with a project benefit and risk analysis.

Chapter 5 presents an overview of the study on the feasibility of braided FR beam structures to be employed on buses.

Chapter 6 details the work packages carried out in order to investigate the feasibility of utilisation of lightweight polycarbonate glazing within the bus industry.

Chapter 7 presents a review of the innovation and value that were delivered as a result of this research programme. Additionally, a critical review of the proposals and research carried out is presented. Finally, direction for further development of the work presented here is suggested.

# 2

# STATE-OF-THE-ART REVIEW OF LIGHTWEIGHTING IN THE BUS INDUSTRY

This chapter investigates the scope, impact and implementation opportunities for lightweighting technology within the bus industry. A state-of-the-art review was carried out by critically analysing peer reviewed journal articles, industry reports as well as public domain information on main bus manufacturers and industry-related tier 1 suppliers.

The state-of-the-art review had two primary objectives:

- **Definition of the impact of lightweighting on the bus industry:** Firstly, an introduction to the bus industry and the relevance and importance of lightweighting within the industry is presented. The benefits, impacts and necessity of lightweighting of buses are reviewed. Barriers and challenges of lightweighting within the industry are introduced.
- **Identification of lightweighting technologies applicable to the bus industry:** A literature review on technologies currently utilised in order to lightweight buses is presented. An extensive survey of most academic studies carried out in relation to bus structures as well as a review of relevant information from bus manufacturers that is available on the public domain was carried out. A review of lightweighting technologies within other industries that could be carried over onto the bus industries is presented.

This state-of-the-art review formed the basis of an evaluation of the current structures and lightweighting status of ADL's buses as well as aid in the identification of new lightweighting opportunities to be further investigated.

## 2.1 Brief overview of the bus industry

Buses are the most widespread, and sometimes the only available, form of public transport, particularly in rural areas. In the UK alone, in 2014/2015, a fleet of around 36 thousand buses covered a total of 2507 million kilometres whilst carrying out 4.7 billion passenger journeys, three times the total number of trips made by rail [4, 5]. Within the EU, more than half of the passenger journeys made by public transport were serviced by one of a fleet of around 800,000 buses, minibuses and coaches covering 500 billion passenger kilometres [6]. Worldwide, it is estimated that there is an annual demand for 664,000 new buses (2018) with a total of more than 8 million buses in circulation [7].

Buses have an important, significant and beneficial impact on society. A recent UK study reported an industry turnover of £5 billion and returns over £2.5 billion in additional economic benefits against a public investment of £0.5 billion [5]. As the world becomes less rural with cities constantly growing in size and population density, buses will become ever more important for an increasing proportion of our society. In London, a city with an extensively developed underground rail system, around 7,500 buses carry 6 million passengers every weekday – twice as much as the London Tube [8]. The demand for bus services is predicted to rise further at an estimated compound annual growth rate (CAGR) of 8.6% [9].

The bus industry is also responsible for significant adverse effects. Globally, buses account for 4% of the total transport energy consumption, which equates to 88 million tonnes of oil equivalent (MTOE) of energy each year. Put into context, this is almost half the total energy consumed by either the aviation or marine industries and more than that consumed by the rail industry [10]. Directly related to this energy consumption are $CO_2$ emissions which in the UK alone would be equivalent to the electricity consumption of 1.67 million households [11]. Additionally, buses are a significant source of air pollution ($NO_x$ and particulates) and noise pollution at urban centres where their operation is typically concentrated. Air pollution has extremely adverse health implications causing between 40,000 and 50,000 early deaths a year within the UK [12–14].

The bus industry has undergone significant transformation in order to increase its sustainability. Intensive investment in clean drivetrain technologies have resulted in significant improvements during the last decade. In 2016, $NO_x$ from a Euro 6 diesel bus were less than from a Euro 6 diesel car (Note: this is on a per vehicle basis, buses are equipped with advanced exhaust after-treatment equipment) [15]. The statistics are even more compelling when considering that in the UK, the average bus occupancy is 11.6 passengers [16] whilst that of a car is 1.57 (2015-2016) [17]. The bus market is currently dominated by diesel internal-combustion-engine (ICE) drivetrains, with other drivetrain technologies including liquefied petroleum gas, hydrogen fuel-cells, hybrid-electrics and battery-electric-buses (BEB) being trialled and introduced in operational services. Industry forecasts indicate a steadily increasing shift from diesel towards full electric drivetrains [18], with the world's second largest bus manufacturer, Daimler AG. claiming that 'by 2030, 70% of city buses will be electric' [1]. The introduction of electric buses is being significantly accelerated following the so called 'VW diesel emissions scandal' of 2015 that revealed serious discrepancies between legislated and real-life emissions of cars [19]. This moved the focus away from $CO_2$ emissions and onto toxic emissions. Rigorous testing legislation existing within the bus industry means that an equivalent to the VW diesel scandal is almost inconceivable [15], however local governments are actively incentivising the introduction of electric buses in order to deal with the public's negative perceptions of diesel as well as dealing with local air-quality issues. Additionally, as the cost of battery technology is reducing, low total lifecycle costs of BEBs will increase their economic viability. In fact, a 2017 study concluded that in spite costing an average of £200,000 more than an equivalent diesel bus, BEBs already have the lowest total lifecycle ownership costs of all existing bus drivetrain configurations [20].

Whilst the main technological advancement focuses on advanced drivetrains, lightweighting is the primary bus structure technology that could compliment the positive advances made within drivetrain technology. Additionally, lightweighting technologies play a key role in assisting, enabling and enhancing the implementation of these emerging drivetrain technologies. This was highlighted by three separate major strategy reports prepared for UK, US and EU authorities which concluded that lightweighting is the main bus structure technology that would result in reduction of both lifetime energy consumption and emissions [21–23].

## 2.2 An overview of lightweighting within the bus industry

Lightweighting, or mass reduction, is becoming an increasingly important design strategy in the transportation industry in order to address its sustainability. The underlying concept is relatively simple. Accelerating or decelerating a mass involves the conversion and the explicitly related loss of energy, hence, a lightweight 'equivalent' system is generally more efficient. This increase in efficiency could in turn be exploited by the designers of the system to achieve better performance, or even facilitate further lightweighting through downsizing of certain components of the system (e.g. if the bus body weight is sufficiently reduced, a smaller lighter powertrain could be used).

Although lightweighting has been one of the most active research topics in design engineering in recent years, it is far from being something new. The aerospace industry started using lightweight metals (aluminium) as early as the 1920's, and in the 1940's De Havilland introduced for the first time sandwich composites in a powered aircraft utilising balsa-wood core plywood sandwich panels in the fuselage of the Comet Racer and the Albatross and later as fuselage-skin structural panels in the de Havilland Mosquito [24]. Yet, as stated by the EU's Directorate General for Mobility and Transport, reducing costs whilst increasing the robustness and availability of lightweighting materials and architecture are the challenges for the decades ahead [25].

Lightweighting could yield a significant impact on reducing the environmental impact of the bus industry with consequential benefits to all the stakeholders, specifically in the following areas:

- **Reduction of energy consumption:** One of the main drivers for lightweighting of a bus structure is the reduction of energy consumption and therefore lifetime running cost.
- **Reduction of $CO_2$ emissions:** Directly related to the reduction in energy consumption is a reduction in emissions. Lightweighting of bus structures could in certain instances enable bus manufacturers to comply with legislative obligations or achieve tax-incentivised certification such as the UK based 'Low Carbon Buses' certification [26].
- **Capacity issues:** Another significant driver for lightweighting is the legal curb weight limit of vehicles and as of consequence the maximum passenger capacity of a bus. The bus passenger capacity is equal to the difference between the curb weight legal limit and the net empty weight of the bus (defined as unladed weight ULW). As such, a lightweight bus will have a higher legal passenger capacity.
- **Increasing demand for on-board systems:** Lightweighting could help offset the weight increase of buses as a result of an ever-increasing demand for more safety, entertainment and comfort systems.

- **Vehicle performance:** Acceleration and rate of hill ascent are affected by the bus weight. A lighter bus would tend to have better performance which could yield a reduction in trip time which is an important factor for bus user satisfaction [27].
- **Vehicle centre of gravity (COG):** The reduction in weight of bus structures above the bus COG level will generally improve passenger ride comfort and reduce risk of roll-over accidents.

However, there are a number of barriers to the uptake of lightweighting technologies:

- **Cost:** The main obstacle to lightweighting is generally the associated cost increase [28]. Lightweighting projects typically necessitate investment in research, design, manufacturing capability and/or component material and manufacturing costs. Lifecycle cost analysis should be taken in consideration, but frequently initial cost investment is still a barrier.
- **Availability of raw materials and supply chain issues:** Besides the cost of lightweight materials and the relevant development, there are generally significant challenges within the supply chain. Capital investment in tooling and training in order to change current materials and manufacturing methods could also make a lightweighting project infeasible.
- **Brand image:** A novel lightweighting project would typically have an associated risk to company and brand image if a lightweight product or upgrade is negatively perceived by customers. Uncertainty about, or a reduction in, reliability or durability are a real barrier within what tends to be a conservative industry. Inertia against radical change exists within both, the manufacturing and the operator's side of the bus industry.
- **Adverse effects and incentives:** Government and local authorities' subsidies on operational costs, which are offered to operators as an incentive to operate commercially infeasible routes, tend to reduce the benefits of capital investment in lightweighting technologies.

The numerous factors above illustrate the complexities behind a lightweighting project. For any lightweighting project to succeed, the primary motivations need to be thoroughly investigated in order to ensure an ultimate net benefit for the stakeholders involved [29]. The next section will illustrate how the driver for lightweighting has shifted during the last decades and seek to indicate what trends are expected in the near future.

## 2.3 History of lightweighting within the bus industry

Lightweighting within the bus industry is not a recent trend. Possibly the first lightweighting exercise within the bus industry took place in Norway in 1927 at Strømmens Værksted A/S [30]. The lightweighting project, which achieved a 26% weight reduction, was necessary as the American designed bus was too heavy to operate on the Oslo road network and would have caused damage. The engineers combined the existing monocoque principle from the American steel bus together with knowledge transferred from the use of aluminium within the British aerospace industry and, in 1929, designed and built the world's first lightweight aluminium monocoque bus weighing 6450 kg. Five years later, a second iteration of the design was completed and the model nicknamed the 'hippo' bus as shown in Figure 2.1 was launched weighing a mere 5080 kg and capable of carrying a passenger load equal to 90% of its curb weight. Another important lightweighting exercise took place during the 1950's when one of the most iconic buses of all times, the original Routemaster, was conceived. A lightweight design was specified as the most important design criteria as this would increase passenger capacity and reduce fuel consumption. The innovative lightweight design consisted of an integrated monocoque structure consisting of an all-aluminium stressed skin construction integrated with two separate steel chassis sections (Figure 2.1), utilising design and manufacturing techniques adopted from the aerospace industry. The bus weighed 750 kg less than its predecessor, giving an increased capacity of eight passengers, and returned a fuel economy that was superior to most of its competitors and successors [31].

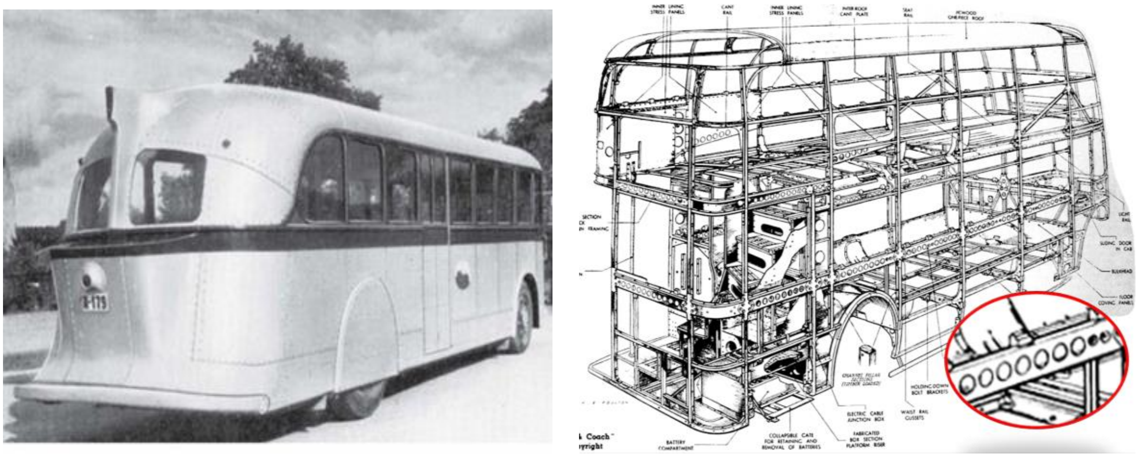


Figure 2.1: Left: The lightweight 'hippo' bus, manufactured in Norway in the 1930's [30]. Right: The main structure of the 1958 'AEC Routemaster', reproduced from [32].

The high-capacity version of the Routemaster had a bus to passenger weight ratio of around 108 kg/passenger, lower than most modern buses including the 2014 ADL Enviro400 DD bus at approximately 115 kg/passenger. Similar to the trend in the automotive industry, the weight of buses and coaches has been steadily increasing over the past decades. This was driven by various factors including demands for increasing passenger safety and comfort levels, increasing size, complex drivetrain systems, and increasing number of on-board systems such as WIFI, CCTV, Next Destination Information, etc. [33]. Advances in engine technology meant that engineers were no longer limited by the power output of engines, and hence it can be argued that the main driver for lightweighting for the past decade has been the reduction of energy consumption results in reducing operation costs and emissions.

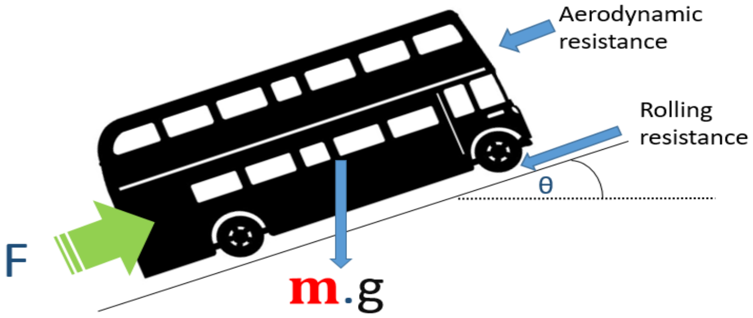
The next step-change in bus weight will be brought about with the arrival of the battery electric buses (BEB). In order for an electric bus to have an autonomous range of around 250 km, a 300 kWh battery pack is necessary [34]. At a systems level, current technology (2015) is allowing an energy density of about 100 Wh/kg [35]. This would mean that a Li-Ion battery system on an electric bus with enough range for a typical full day operation without recharging would weigh in excess of 3000 kg. In order to comply with gross vehicle weight (GVW) restrictions, bus manufacturers are having to sacrifice passenger capacity in order to accommodate the required battery packs. Lightweighting technology is key in reducing the bus weight in order to regain the passenger capacity that was sacrificed in order to accommodate the battery packs on these BEBs.

## 2.4 Quantification of the benefit of lightweighting

In this section, an evaluation of the primary motivations for lightweighting within the bus industry both in the current and near future scenarios is presented. Finally a quantification of the expected benefits is presented.

### 2.4.1 Reduction of energy consumption through lightweighting

There are four main contributors to the energy consumed in order to move a bus. These are resistance against rolling, acceleration, gravity and aerodynamic based forces as illustrated in Figure 2.2.



$$F = \mathbf{m}.\left[\underbrace{gC_{rr}}_{\text{Rolling resistance}} + \underbrace{C_{r.i.}\,{}^{dv}\!/_{dt}}_{\text{Acceleration}} + \underbrace{g\sin\theta}_{\text{Gravitational resistance}}\right] + \underbrace{C_f v}_{\text{Drivetrain frictional resistance}} + \underbrace{0.5\rho g C_D A v^2}_{\text{Aerodynamic resistance}}$$

Figure 2.2: The influence of the mass (m) of a bus on the total resistance forces (F) where $C_{rr}$ - coefficient of rolling resistance, $C_{r.i.}$ – multiplier to account for the equivalent mass of the rotational inertia lumped at vehicle's c.o.g, $dv/dt$ - acceleration, θ - slope, $C_f$ - coefficient of friction within drivetrain, $C_D$ - drag coefficient, A – bus frontal area, v – velocity.

Except for aerodynamic resistance, the other elements of resistance all depend on the mass of the vehicle (m), and by reducing the vehicle mass, these forces and the related energy consumption are reduced. Given that the typical bus operation consists of a low average speed, with frequent stop-and-go patterns, the effect of aerodynamic resistance is less important.

Numerous studies seeking to quantify the fuel consumption reduction brought by lightweighting of a typical diesel bus claim that 5% to 7% reduction in fuel consumption is experienced per 10% lightweighting [36–41]. However, as the drivetrain of a battery-electric-bus allows for kinetic energy recovery during deceleration, the direct benefit of lightweighting in terms of energy consumption reduction is reduced to 2% to 5% reduction in energy consumption per 10% lightweighting [41–43]. However, the weight reduction could also lead to a reduction in battery pack size hence, providing an additional indirect cost benefit of lightweighting [44, 45].

### 2.4.2 Passenger capacity

In order to limit the damage to roads exerted by excessive loading, countries around the world impose a maximum limit on the gross vehicle weight (GVW) i.e. the maximum operating weight of a bus (includes chassis, body, engine, engine fluids, fuel, accessories, driver, passengers and cargo). This limits the maximum axle loading capacity of a vehicle.

Lightweighting the bus structure can thus increase the passenger capacity, although passenger capacity is also limited by safety legislation regarding the number of doors available on a bus. However, the significant weight of batteries required on-board for the operation of electric buses has had an important detrimental impact on passenger capacity and hence lightweighting technology is critical in recovering lost passenger capacity. Additionally, as the average weight of the general population increases, legislators are seeking to increase the 'legal' average weight of passengers hence aggravating the issue of passenger capacity reduction [46].

### 2.4.3 The economics of bus lightweighting

Within the automotive industry, the generally accepted economically feasible limit (increase in cost for the manufacturer) for car lightweighting is about £2-5 per kilogram of weight reduction [47]. Buses typically cover more than one million kilometres in their lifetime, the majority of which being inefficient city stop-go profile driving and hence, it is expected that the lifetime benefit is significantly higher than that of the general automotive industry. Assuming the average values as detailed in Table 2.1, the author proposes that for a typical diesel bus, an investment of up to £15/kg lightweighting is economically feasible.

Table 2.1: Calculation of economically feasible lightweighting of a diesel ICE bus.

| | |
|---|---|
| Average fuel consumption: | 40 litre/100 km |
| Specific fuel saving (litre/(100 km*100 kg)): | 0.15 litre/(100 km*100 kg) |
| Lifetime performance: | 1,000,000 km |
| Lifetime fuel savings: | 15 litre/kg lightweighting |
| Average net cost of diesel fuel in UK (2010 – 2017) [48] | £1.00/litre |
| Economically feasible lightweighting (diesel bus): | £15/kg lightweighting |

In the case of BEB, although the direct cost benefit of reduction in energy consumption is lower than that of diesel buses, there is a significant cost benefit related to the downsizing of the battery pack that effective lightweighting would enable. Hence, in the case of BEB, assuming the average values as detailed in Table 2.2, the author proposes that for a typical BEB bus, an investment of up to £17/kg lightweighting is economically feasible.

Table 2.2: Calculation of economically feasible lightweighting of a battery electric bus.

| | |
|---|---|
| 10% lightweighting of 12 tonne Enviro200EV | 1200 kg |
| Reduction in battery energy consumption | 5% |
| Reduction in cost battery pack size<br>(assuming 5% cost reduction of battery pack) | £12,500 |
| Lifetime electrical energy savings | £8,212 |
| (assuming daily recharge of 300 kWh pack) | £15/kWh |
| Economically feasible lightweighting (BEB): | £17.2/kg lightweighting |

These derived economic benefits of lightweighting are only intended to be used as an initial indication of the feasibility of a proposed project. Feedback collected from UK bus operators indicated that although they actively seek to invest in technologies that would yield a lifetime cost reduction, on average, the longest payback period on a technology investment they would consider feasible is seven years [49]. Hence, bus manufacturers would be hesitant to consider lightweighting projects at the cost derived particularly in projects whose absolute weight saving is relatively small. On the other hand, legislation changes could make even higher investment in lightweighting feasible. Delivering a bus with superior passenger capacity could be a make-or-break factor within a buying decision and a bus manufacturer might justify investing more than the derived amounts in order to achieve such a competitive advantage.

The derived quantified benefit of lightweighting is in line with the claims of an extensive study published in 2015 by Ricardo plc. The report prepared for the EU commission, investigated the scope of lightweighting in improving energy efficiency of buses and concluded that in the near-future period up to 2030, the weight of a bus could feasibly be reduced by 14% at an investment of about £19/kg as detailed in Figure 2.3 [23].

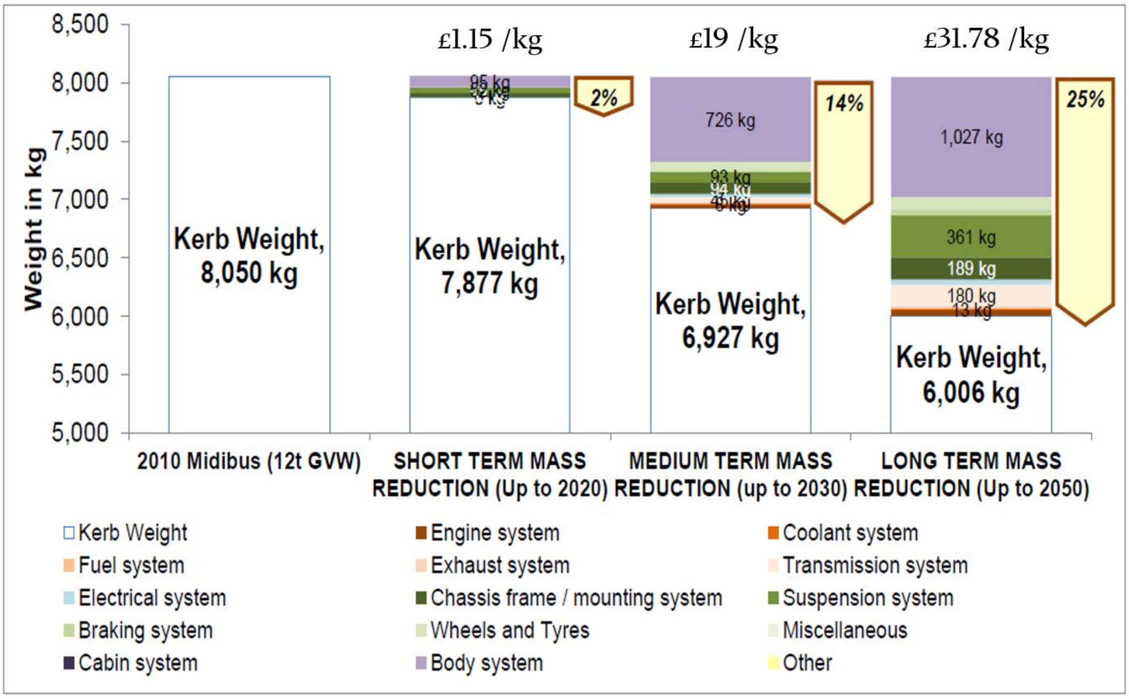


Figure 2.3: Forecast lightweighting potential and cost for a typical single-deck bus, reproduced from [23].

## 2.5 Review of the application of lightweighting technology

The main drivers and benefits of lightweighting were investigated in the first half of this chapter. In this section, technologies which could feasibly achieve lightweighting within the bus industry are reviewed. Firstly, the boundaries of this review are defined, and then various technologies, case studies and lightweighting projects which could be applicable to ADL's buses are discussed.

### 2.5.1 The fundamentals of lightweighting technology

In the ideal lightweighting scenario, the weight of a system is reduced without adversely affecting any of the necessary functionalities, properties and total cost over the whole lifecycle of the system.

At a fundamental level, lightweighting of systems is possible if the material within that system is not being exploited to its limit [50]. This could be achieved through:

- **Design integration:** Supporting multiple loads/achieving different functions with one structure.

- **Design verification:** Ensuring correct specification of loads and design requirements thus avoiding overdesign.
- **Design optimisation:** Changing the shape and cross-section of the structure so that material is concentrated along the paths of loading.
- **Optimal choice of materials and manufacturing methods:** The combination of materials and manufacturing techniques that would allow the optimal lightweight design to be realised.

### 2.5.2 Definition of the scope of bus-applicable lightweighting technology

The state-of-the-art review was limited to the lightweighting of bus primary structures (chassis and body structures), body frame enclosures (body panels and glazing) and primary ‘static’ structures such as seats. The drivetrain and other on-board systems are considered out of scope as ADL does not design or manufacture the majority of these systems and hence, influence on their design is limited.

Traditionally, the bus industry consisted of a few main chassis suppliers (e.g. Volvo, Daimler or Scania) who manufactured and sold structurally integral chassis structures onto which separate bus body manufacturers build the main bus body. This typically leads to redundant structural strength and the opportunity of significant lightweighting. The vast majority of chassis structures consist of a ladder-type frame of welded steel tube sections whilst the body spaceframes are typically manufactured from folded tubular steel or extruded aluminium box sections. The current state-of-the-art lightweight bus structures have a semi-monocoque structure. The assembled chassis, body frame and skins form the bus superstructure and are all essential to providing the required strength, bending stiffness and torsional stiffness [51]. The chassis structure consists of a welded steel structure, whilst the body frame is a mechanically assembled aluminium extrusion frame with high-strength steel (HSS) structures used in regions of high strength requirements [23]. An example of such a structure, which is also representative of a typical ADL bus structure, is shown in Figure 2.4. This consists of a welded steel chassis (black) and a predominantly aluminium extrusion body (grey) which form the bus semi-monocoque superstructure. Outside panels, glazed doors and windows are then bonded onto the superstructure to form the main bus structure.

Figure 2.4: Typical structure of the state-of-the-art in lightweight bus structures, reproduced from [52].

There are two main lightweighting strategies, which could be applied specifically to the general bus structure:

- **Design optimisation:** This consists of optimising the current design (profile, gauge and location of the main structural elements) without changing current materials and/or manufacturing techniques. Increasing computational power and simulation accuracy of computer aided design (CAD) software are enabling engineers to identify optimum design solutions within acceptable time and economic constraints.
- **Material, manufacture and assembly method substitution:** The optimum lightweight design solution is achieved by first running topology studies which are only restricted by the necessary design volume. Subsequently materials and manufacturing method combinations which would allow the engineer to design a structure that resembles the organic structure obtained from the topology studies whilst still respecting all the necessary design parameters including cost boundaries need to be identified. As such, this second degree of lightweighting usually necessitates the change of materials and/or manufacturing methods.

### 2.5.3 Structure design optimisation for lightweighting

The primary structural elements within the bus structure are box section beams. Advances in design optimisation software are making it possible to optimise the dimensions and wall thickness of every single beam within the structure in order to achieve a global weight reduction of the system. Various research and industrial studies showed that weight reduction of 4% to 5% of the bus superstructure is possible by running such optimisation programmes in order to define the optimum sizing of individual beams whilst retaining the same materials and manufacturing techniques [53–56].

In order to achieve a higher degree of lightweighting, topology optimisation of the design is typically necessary. This consists of a mathematical approach that optimises material layout within constrained volumetric boundaries for a given set of loadings and constraints to achieve a prescribed set of targets. This design process was followed during a $5 million research programme commissioned by the US Federal Transit Administration intended to develop a lightweight modern having significantly reduced fuel consumption [57]. The first step in the design of the bus superstructure consisted of defining the design space and shape constraints (e.g. drivetrain mounting points) as shown in Figure 2.5.

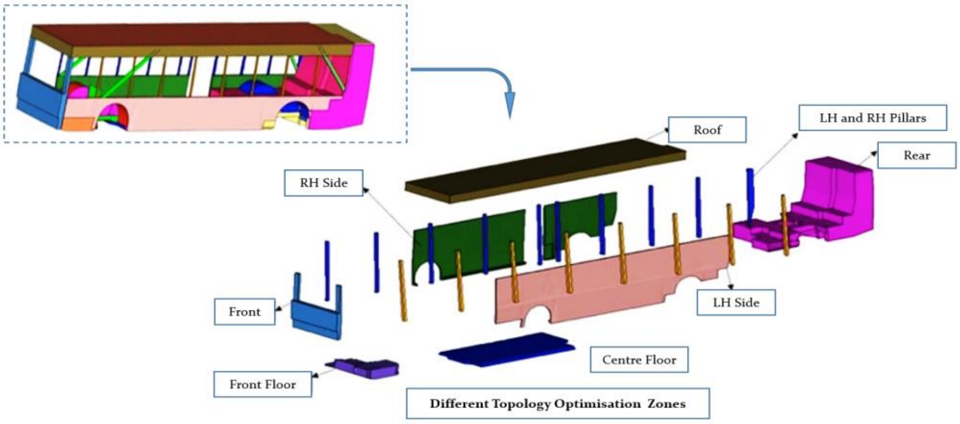
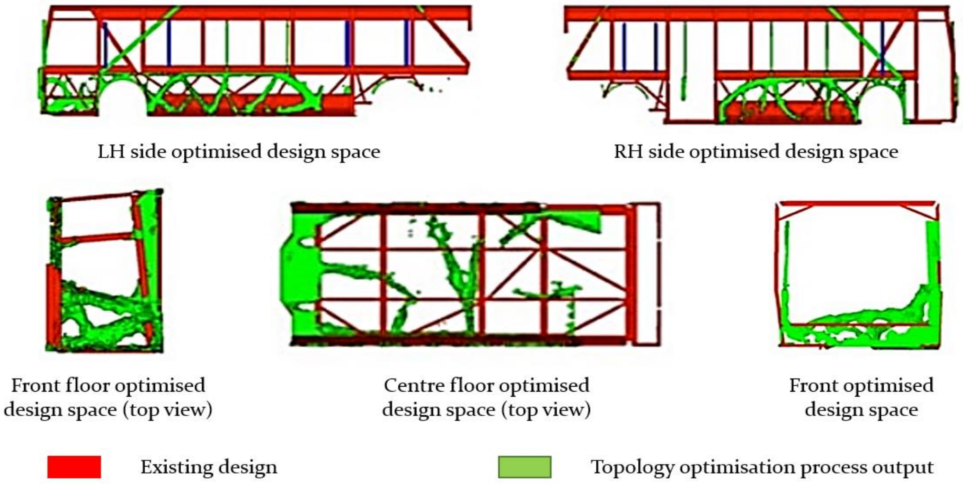


Figure 2.5: Defined design space for the topology analysis of a typical bus superstructure, adopted from [57].

In a second step, the necessary load cases (e.g. static gravity, operation dynamic loadings and passenger loadings) are applied to the model and the topology analysis carried out with typical results shown in Figure 2.6.


LH side optimised design space

RH side optimised design space

Front floor optimised design space (top view)

Centre floor optimised design space (top view)

Front optimised design space

🟥 Existing design
🟩 Topology optimisation process output

Figure 2.6: Results of topology optimisation study of a bus monocoque structure, adopted from [57].

The results yield organic shapes, which if they were possible to manufacture economically, would yield the ultimate lightweight structure. However, these topology results need to be translated to take into consideration material and manufacturing constraints which, in this case, were defined during initial feasibility studies to be aluminium extrusions [58]. The final outcome of the topology optimisation is illustrated in Figure 2.7. The final step consisted of a beam gauge and shape optimisation in order to define the details of the various beams.

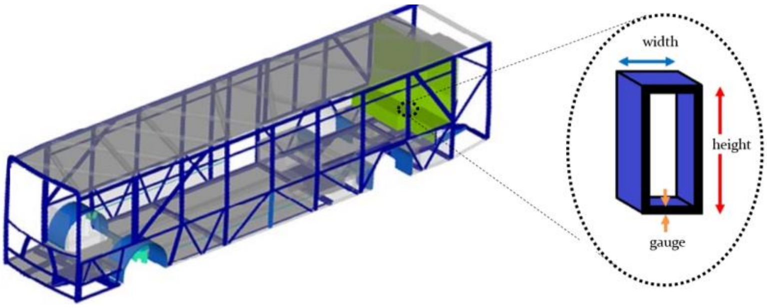


Figure 2.7: Final design outcome of the topology optimisation. Inset showing parameters of the bus beam structure that were optimised in the final beam gauge and shape optimisation process, adopted from [57].

The design envelope as well as material and manufacturability constraints severely limit the functionality of high level bus structure topology optimisation. However, topology optimisation lightweighting could be highly effective at component level. A lightweighting research programme conducted by Hyundai Buses, concluded that 21% lightweighting of their current steel body frame was possible by adopting an optimised aluminium frame structure. Sensitivity analysis techniques were used in order to identify critical components which need optimisation. Components whose shape could be feasibly modified such as the cantrail beam extrusion were optimised utilising topology optimisation. The frame structure was lightweighted by optimisation of the gauge, shape and size of mechanical connectors as illustrated in Figure 2.8 [59].

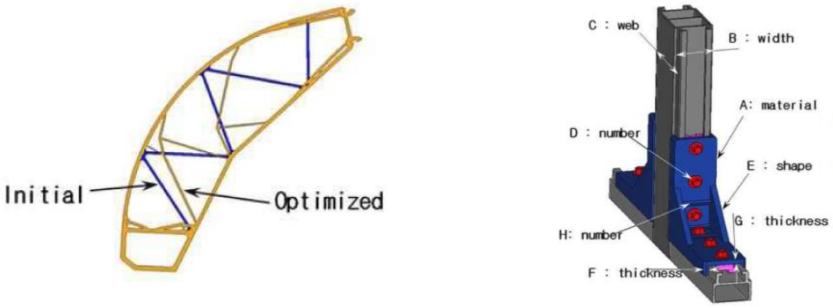


Figure 2.8: Left: Shape topology optimisation of the cantrail beam. Right: Sensitivity analysis on the critical parameters (A-H) of a mechanically joined aluminium extrusion bus body utilised to define the optimum lightweight configuration, adopted from [59].

### 2.5.4 Lightweighting through the utilisation of advanced materials

Although design optimisation could achieve a degree of lightweighting, a change of the materials used to manufacture the system would be necessary. This would typically necessitate changes in manufacturing assembly of the structure.

#### 2.5.4.1 Advanced metals

The three different metal alloys that are predominantly utilised within the bus industry are carbon steel, stainless steel and aluminium. The vast majority of buses currently in operation around the world have a steel-based chassis structure. The body frame is either constructed of a welded steel tube (folded and welded) frame or utilising aluminium extrusions which are generally assembled using mechanical joints (rivets and bolts) [60]. Steel body frames are typically made by metal active gas (MAG) welding of rectangular hollow section (RHS) profiles and are the most common frame structures particularly in emerging markets. The introduction of stainless steel in the bus industry is typically based on corrosion resistance properties which allow for increased lifetime of the frame although their higher strength could also be exploited for lightweighting purposes [61]. An aluminium body frame is favoured when lightweighting is a key driver with recent industry strategy reports stating that a steel chassis and aluminium body frame is the current state-of-the-art lightweight bus structure [23]. However, there is a lack of evidence that an aluminium based body frame yields the lightest commercially-feasible bus structure. Publicly available studies comparing bus superstructures based on different metal solutions tend to compare the proposed solution to a datum steel structure. A study presented by the Brazilian bus manufacturer Marcopolo showed that by replacing the standard frame structure steel from a 230 MPa YS mild steel to a 380 MPa HSS, an 18.8% lightweighting of the bus frame was achieved [62]. Another almost identical study was carried out by the Indian market leaders Ashok Leyland stating 13% lightweighting by upgrading to HSS (YS of 320 MPa) [63]. A study conducted by Hyundai Buses evaluating the lightweighting potential of aluminium, showed that 21% lightweighting is possible by replacing mild steel by an aluminium bus frame structure [59].

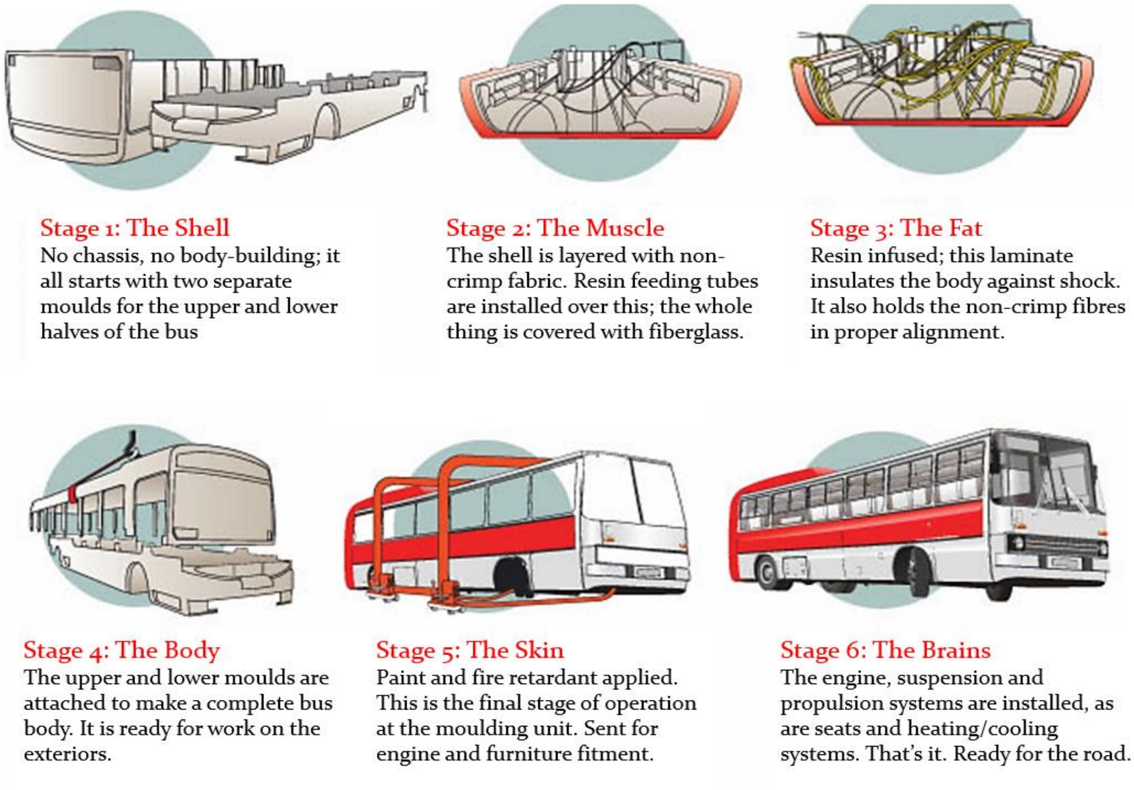
An analysis of the buses currently available on the European market shows a split on the choice between aluminium and steel based body frame structures. Whilst some of the leading European bus manufacturers such as ADL, VDL [64], Volvo [65] and IRIZAR [66] are opting for mechanically joined aluminium body frames, others such as Solaris [67] and Mercedes [68] are opting for advanced steel body frame structures.

Although the majority of research on bus lightweighting is focused on the bus superstructure, some research on lightweight of secondary structures such as passenger seats has also been conducted. One study claimed an aluminium bus seat weighing 8.13 kg was 35% lighter than the original steel-based design [69], whilst another study claimed 20% lightweighting was achieved through the utilisation of HSS resulting in a 9 kg seat structure [70]. Another study claimed a 5.9 kg double seat structure was feasible through the utilisation of a cast magnesium structure [71].

#### 2.5.4.2 Polymer and composite materials

The second family of materials which offers significant lightweighting potential for bus structures are composite materials. Composite materials are materials made up of two or more sub-materials with different physical and/or chemical properties which when combined, result in a material with properties different from those of the individual constituents. There are various sub categories including fibre reinforced composite materials and sandwich structures. Within the aerospace industry, the increasing demand over the last 30 years, for lightweight structures has resulted in the incremental utilisation of composite materials from 5% utilisation on the Airbus A310 up to 53% in the latest Airbus aircraft (A350XWB) [72].

Within the bus industry, there is a history of utilisation of lightweight composite materials and in 1992, the first production bus to be constructed fully out of composites was launched (Neoplan Metroliner) [73]. There have since been other composite intensive bus structures with the most successful being the CompoBus produced by North American Bus Industries (NABI). The bus was developed in a $60 million research programme funded by the US Federal Transit Authority and about 700 buses were sold with production ceasing in 2013 [74]. This bus consists of a fully composite integral body and chassis structure made up of a glass and carbon-fibre reinforced, vinyl-ester resin laminate structure (main production sequence shown in Figure 2.9), onto which the metal suspension and drivetrain systems were mounted directly. The same structure and manufacturing process is the basis for the only significant all-composite bus currently available on the market, the Proterra Catalyst™ whose drivetrain is fully electric [75, 76].



Stage 1: The Shell
No chassis, no body-building; it all starts with two separate moulds for the upper and lower halves of the bus

Stage 2: The Muscle
The shell is layered with non-crimp fabric. Resin feeding tubes are installed over this; the whole thing is covered with fiberglass.

Stage 3: The Fat
Resin infused; this laminate insulates the body against shock. It also holds the non-crimp fibres in proper alignment.

Stage 4: The Body
The upper and lower moulds are attached to make a complete bus body. It is ready for work on the exteriors.

Stage 5: The Skin
Paint and fire retardant applied. This is the final stage of operation at the moulding unit. Sent for engine and furniture fitment.

Stage 6: The Brains
The engine, suspension and propulsion systems are installed, as are seats and heating/cooling systems. That's it. Ready for the road.

Figure 2.9: The construction of all-composite buses: NABI's CompoBus, adopted from [77].

An extensive study on a ten years operational period of NABI's Compobus concluded that the operation of these composite-structure buses was successful and had a lower total lifetime cost than comparable steel buses due to lower maintenance and repair costs [75]. However, currently there is only one significant full-composite structure bus offered to the market by Proterra. The unsuccessful penetration into the market of fully composite bus structures could be attributed to various factors including cost increase, capital investment in tooling, low rate of production and market perception and acceptability. Another critical issue is that a bus manufacturer needs the ability to offer several variations of the same model (length and capacity) and this is typically achieved by having a modular design. Two main variations of achieving this are being investigated and some are being implemented on production buses:

- The first consists of utilising individual composite beam and sandwich panel structures, which are then assembled and bonded. This concept was evaluated in a research collaboration between the Federal Transit Administration and the National Composite Centre in the USA. A thermoplastic sandwich body panel (E-glass/polypropylene skins with polypropylene honeycomb core) which would be bonded onto a FR composite beam structure was proposed. The study concluded that compared to a conventional steel frame and aluminium skin panel, a weight saving of 55% could be achieved [78].

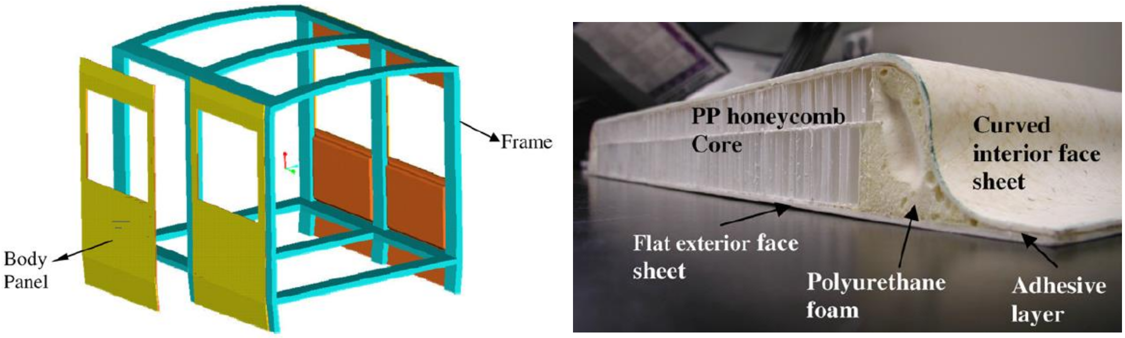


Figure 2.10: Thermoplastic sandwich side panel, adopted from [78].

- The EU funded LITEBUS project evaluated a similar concept. The structure consisted of sandwich panels (made up of fibre reinforced polymer (FRP) skins and foam cores) reinforced with fibre reinforced pultruded frame sections. The programme successfully built a module and demonstrated compliance with bus roll-over structural requirements [79].

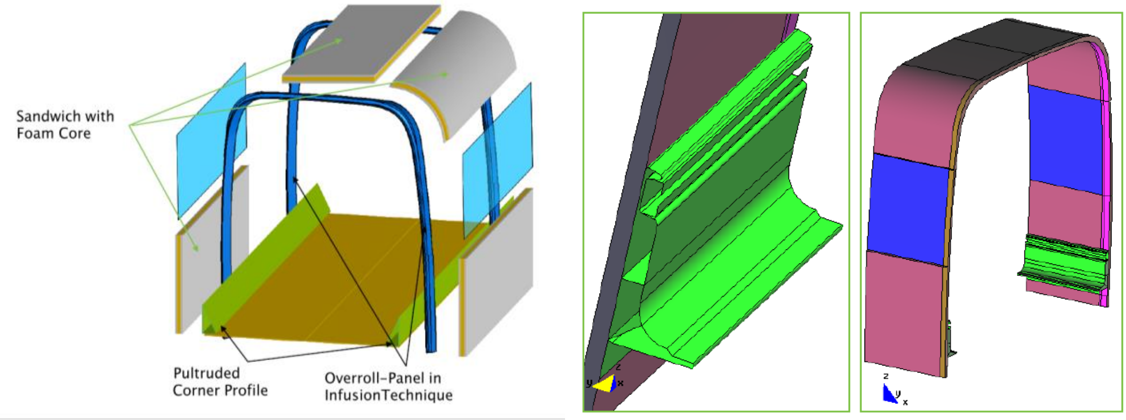


Figure 2.11: The lightweight composite modular frame concept LITEBUS, adopted from [79].

- The second approach consists of utilising composites for the manufacturing of integral sections of the bus where composites could help achieve significant lightweighting potential. An EU funded project concluded in 2014, involving Volvo, researched the rear of a hybrid bus, redesigning it from a metal based module into a sandwich composite module. The prototype was built and confirmed a successful weight saving of 900 kg of the rear module of a bus [80]. This concept was implemented in a production of the Routemaster (new London bus manufactured by Wrightbus). The whole rear structural section is constructed out of thermoset epoxy glass and carbon fibre prepregs and closed cell structural polymer core material, using a composite vacuum-assisted resin infusion in an open one-sided tool as was illustrated in Figure 2.9 [81].

### 2.5.4.3 Lightweighting technologies in other industries

The heaviest component of the bus superstructure is the chassis structure, which is typically around 50% of the total weight. Within the automotive industry, aluminium chassis structures are increasingly being introduced, achieving significant weight reductions. The truck industry is also investigating the feasibility of aluminium based chassis structures. One of the outcomes of the '21st Century Truck Partnership' research programme was a lightweight aluminium chassis (Figure 2.12) developed for Volvo, 40% lightweighting (equivalent to 385 kg) was achieved over the baseline steel frame structure. The frame was built by mechanically joined high strength roll formed aluminium [82, 83].

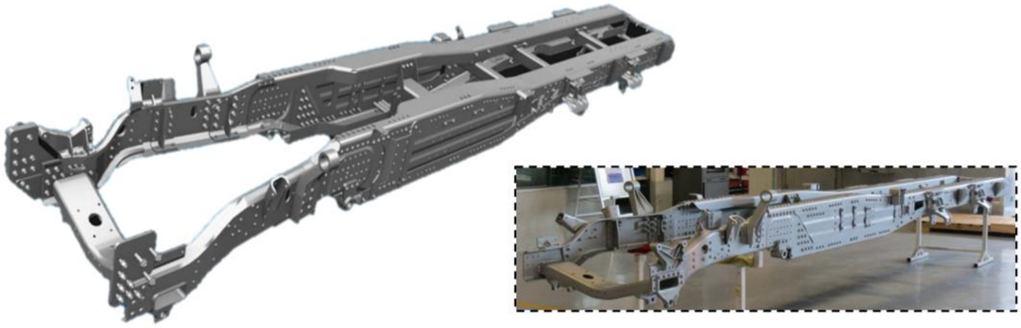


Figure 2.12: Aluminium chassis developed in the Volvo 'Supertruck' project - 40% lightweighting (equivalent to 385 kg) was achieved in comparison to the standard steel chassis, adopted from [82, 83].

Friction stir welding has been used to manufacture an aluminium chassis structure from a series of aluminium extrusions. This process is exploited in various industries including the rail, naval and aerospace industries [84]. Fontaine Trailers in the USA exploit the technology to manufacture the commercially available trailer illustrated in Figure 2.13 [85]. The resulting trailer achieves a 33% weight saving compared to a conventional steel trailer whilst having superior strength and stiffness. The resultant structure is a continuous span of cross members that are friction stir welded, essentially creating a very efficient all-aluminium sandwich panel [86].

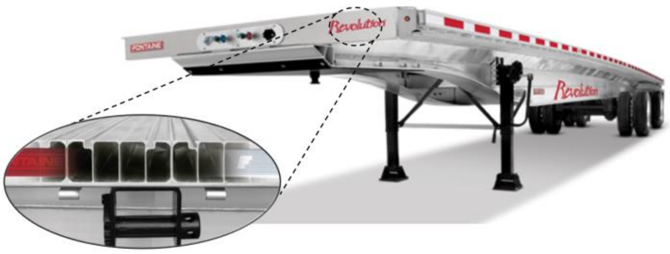


Figure 2.13: Fontaine lightweight aluminium trailer manufactured by friction stir welding of a series of aluminium extrusions is stiffer, stronger and 33% lighter than a conventional steel trailer, adopted from [85].

Finally, a DD bus typically has more than 500 kg of glass glazing. Advanced polymer glazing technologies such as coated polycarbonate glazing could provide the opportunity of around 50% weight reduction [23]. There is a general negative perception on the quality and in-service performance of polymer glazing, however there are various commercial applications of PC glazing within the automotive industry [87–90] and polycarbonate glazing is the predominant glazing material within the forestry equipment industry [91].

## 2.6 Summary of bus lightweighting technology state-of-the-art

The association of project management (APM) states that correct definition of project scope is critical for the success of any project. The scope of this chapter's first section sought to address this issue by evaluating the main drivers for lightweighting within the bus industry. Over the past 90 years, lightweighting technology has played a significant role within the industry. Throughout the decades, the main driver and necessity for lightweighting has shifted significantly. First applications of lightweighting were necessary in order to enable buses to achieve the required performance and or passenger capacity. As road infrastructure and powertrain technology improved, the recent and current main drivers for lightweighting of buses consist of reducing operational emissions, energy consumption and running costs. The advent of the electric bus is going to necessitate and push a step-change in lightweighting efforts within the bus industry. Besides the direct advantages of reduced operational energy consumption that lightweighting offers, a clear competitive advantage will be gained by a manufacturer offering an electric bus with maximised passenger capacity.

Having confirmed the significance, increasing importance and value of lightweighting within the bus industry, the second section of this review consisted of an analysis of the utilisation of lightweighting technology within the industry. Leading industry reports are in agreement that a semi-monocoque structure consisting of a carbon steel chassis and a predominantly aluminium body frame is the current optimum lightweight body structure configuration. Separate studies show that significant lightweighting of welded carbon steel body frame structures could be achieved through the utilisation of HSS structures. However no studies comparing which advanced metal chassis and body frame configuration would yield the lightest bus superstructure were identified. Additionally, although lightweighting is a critically important driver, the choice between aluminium and steel body frames depends on various other factors including cost, body assembly and reparability issues. Whilst most steel body frames are welded, aluminium body frames are typically mechanically assembled. The change from one material to another would imply severe and drastic changes to the supply chain, final assembly lines, repair and maintenance and beyond.

Buses having a composite-intensive structure have also been successfully manufactured. However, commercial success has been very limited possibly due to the high costs. Additionally, a comparison of a currently available full-composite bus with a lightweight metal bus did not show any evident significant reduction of weight. However, the utilisation of advanced composites to manufacture sub-components could offer significant lightweighting potential. The utilisation of structural sandwich panels and integrated composite sub-assemblies could offer feasible lightweighting opportunities.

Aside from the bus superstructure, there are other semi-structural components which could offer lightweighting opportunities with the three most significant being seating systems, glazing and outside body panels. Studies have illustrated the feasibility of weight reduction of seating assemblies. However, there are a number of specialist seating manufacture companies who supply the aerospace and mass transit industry offering various lightweight seating options to the market. The vast majority of glazing currently installed in the bus industry is glass. Polymer glazing could offer the opportunity of significant lightweighting with case studies in other industries claiming that up to 50% lightweighting is possible.

It must be added that a crucial aspect of any effective lightweighting exercise is that a 'true systems approach' needs to be adopted to ensure successful outcomes [92]. The lightweighting of components could not only negatively affect the structural response of related bus structures but could also influence other properties (e.g. thermal or insulation properties) whose negative effect could outweigh the lightweighting benefit.

The scope of this review was that of identifying advanced lightweighting technologies that are either being exploited within the bus industry or could be feasibly translated to the industry. As will be detailed in Chapter 3, this review was used to benchmark ADL buses against what is the current state-of-the-art in lightweight bus structures. Additionally, the review provided a list of lightweighting opportunities that are not currently being investigated by ADL and which were then further investigated during this research programme.

# 3

# IDENTIFICATION OF LIGHTWEIGHTING OPPORTUNITIES FOR ALEXANDER DENNIS LTD.

Chapter 2 presented a review of lightweighting projects about which information is available within the public domain. Whilst this review was being carried out, an analysis of the structure of buses that ADL manufacture was carried out. During this period, ADL was also running a company-wide lightweighting project identification and implementation programme which was partly assisted through this EngD research. The information from the state-of-the-art review, the analysis of ADL bus structures and ADL's ongoing lightweighting projects were combined to create a short-list of possible lightweighting projects.

This chapter details the process of project identification and the initial feasibility studies that were carried out. The process culminated in the evolution of an innovative structure redesign project which promised significant lightweighting potential as well as other benefits. The final section of this chapter introduces this lightweighting opportunity which, following a proposal of the project concept to ADL, was accepted as the main focus for this EngD research programme.

## 3.1 Research methodology

At the beginning of this research project ADL did not specify any particular structure on which the lightweighting effort had to be concentrated. The research envelope was not constrained and was intentionally allowed to diverge so that lightweighting opportunities, which were not being considered or investigated by the company, could be identified. It was hoped that this approach would increase the potential of the research delivering innovative lightweighting opportunities to the company.

At a fundamental level, this EngD research programme is an engineering design process. Design process methodologies are difficult to standardise for various reasons. Part of the reason is the iterative, non-linear nature which is typically necessary and caused by ever changing market conditions and customer needs and preferences [93]. The literature on design process is vast, yet there is no one single model which is agreed to provide a satisfactory and universal description of the design process [94]. The UK's Design Council proposed the double-diamond design methodology, illustrated in Figure 3.1, seeking to propose a methodology that captures best practice and commonalities of creative design processes [95]. The model divides the design methodology in four distinct phases – discover/understand, define, develop/explore and deliver/create. The shape illustrates how the design process must go through two distinct divergent and convergent cycles in order to ensure a creative solution that solves the problem is delivered at the end of the design process.

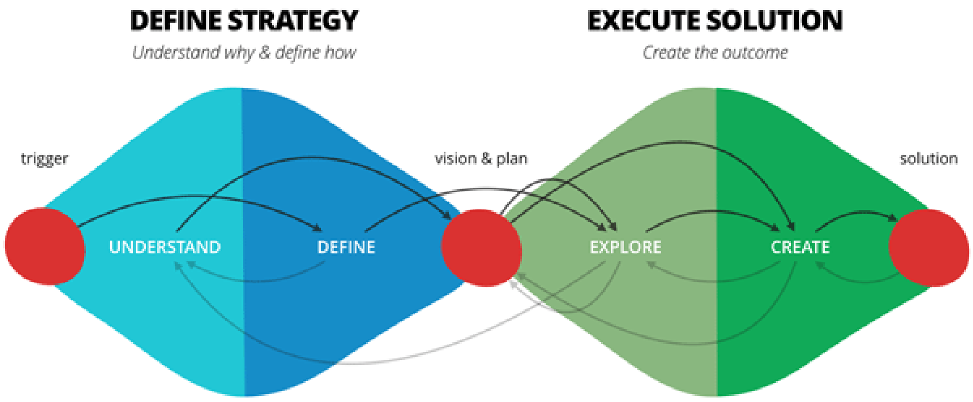


Figure 3.1: Double-diamond design methodology proposed by the UK Design Council, adopted from [95].

The double-diamond design methodology was adopted for this EngD research. The following is an overview of the main activities carried out at the different phases of the design process:

- **Discover (understand) phase:** This critical stage of the process aims to define the problem being addressed. It is a diverging discovery process developing a clear creative brief that frames the fundamental design challenge. Primarily, this consisted of the state-of-the-art review presented in chapter 2. The research of published information was supplemented by various working visits to ADL bus manufacturing plants, a bus operation depot, bus industry trade exhibitions, conferences and seminars.
- **Define phase:** The second phase is a convergent phase, which seeks to filter down the results of the discovery phase in order to define the lightweighting opportunity to be fully developed. Firstly, a detailed analysis of ADL's bus structures and materials was carried out. Information was collected through analysis of the computer aided design (CAD) models and finite element (FE) structural analysis models of the ADL buses. An overview of ADL's lightweighting strategies and ongoing projects was also conducted. This information led to the filtering of lightweighting opportunities identified in the state-of-the-art review to yield a list of lightweighting opportunities which could be developed during this project.
- **Develop (explore) phase:** The develop phase consists of the creation, development, testing and feasibility analysis of proposed solutions. During this EngD various feasibility studies on different possible lightweighting opportunities were carried out. These created feedback which led to the final lightweighting proposal, which was taken forward for further development and intended delivery.
- **Delivery (create) phase:** This is the final stage where the resulting solution is created and developed until the product is launched. During the detailed design definition of the proposed lightweight upper-deck structure, two proposed technologies required further research and development work. Research carried out on fibre reinforced composite beams and polycarbonate glazing led to the successful manufacture of demonstrator components.

This chapter will provide an overview of research and feasibility studies carried out during the 'define' and initial 'development' phases this EngD. As illustrated in Figure 3.1, it is typical that during the design process, initial development of proposed solutions create feedback information that refines the decisions made during the define phase. As will be detailed in this chapter, the various feasibility studies which were carried out were essential in defining the opportunity with the most significant lightweighting potential.

## 3.2 Analysis of ADL and ongoing lightweighting projects

### 3.2.1 The EngD sponsor company: Alexander Dennis Ltd.

Alexander Dennis Ltd. is a British company which could be considered a phoenix born out of the ashes of three historic British bus, coach and truck manufacturing companies: Dennis (founded 1895), Alexander (founded 1947) and Plaxton (founded 1907). Since its formation in 2004, with the acquisition of Plaxton completed in 2005, the company has become the fastest growing bus and coach builder in Western Europe, employing more than 2,000 people at facilities in the UK, continental Asia and North America [96].

ADL has the technical capacity to design and manufacture both bus chassis and body and has been actively seeking partners around the world as they seek to expand production. ADL specialise in designing and supplying fully optimised products targeting the market of low-floor buses, in particular DD buses whose high capacity to footprint ratio is gaining worldwide attention. ADL produced around 2600 buses in 2015, which is approximately 1% of the world's full-size bus and coach demand [96]. ADL is intent on continuing with its aggressive growth strategy, aiming at exceeding £1 billion in sales by 2020. The growth is expected to come mainly from the export market which is driven by the success of the DD bus platform [96]. Given the strategic importance of the DD bus for future growth of the company, it was agreed with ADL to focus this research on the DD bus configuration.

### 3.2.2 ADL range of buses

The whole range of ADL buses are based on three different platforms: the Enviro200 (a single-deck low-floor bus), the Enviro400 and Enviro500, both DD buses. The buses are in operation in numerous countries around the world as illustrated in Figure 3.2. Within every platform, there are two primary variants. The first difference is the overall length of the bus which can vary by up to 30% (8 m – 12 m). This variation in length is facilitated by having a modular bus structure, where the front and rear sections of the bus are common structures within a bus range and the middle bus structure is extended to achieve the various length offerings.

Figure 3.2: ADL's range of low floor buses are based on three different platforms; two-axle single-deck bus (Enviro200), two-axle double-decker bus (Enviro400) and triple-axle double-decker bus (Enviro500), reproduced from [97].

The second variant is the type of drivetrain. ADL designs, manufactures and assembles buses equipped with Euro VI diesel drivetrains, gas (compressed natural gas), and also various types of IC/electric hybrids. The different drivetrains typically necessitate some modifications of the bus structure however, the most significant changes of the bus structure will be due to the shift to battery-electric drivetrains. In 2015, ADL partnered with the world's leading electric bus manufacturer, BYD, and supplied the biggest fleet of single-deck electric buses within Europe to London in 2017 [98]. ADL does not yet offer an all-electric DD bus. Yet, some competitors are starting to offer such an option to the market. In March 2016, a fully electric DD bus built by BYD started trials in London [99], whilst in June 2018 one of ADL's main competitors, Optare, won an order for 12 electric DD buses from Transport for London (TFL) [100]. In the same month, a Canadian start-up company called Greenpowerbus leased a trial triple-axle fully electric DD bus, the EV550 [101], to a Canadian operator. Following this, in July 2018, ADL announced a partnership with Proterra (USA) to supply DD bus structures for the Proterra electric drivetrain [102].

Lightweighting is one of the key innovations identified by ADL which would facilitate the shift towards the electrification of the drivetrain being experienced by the industry. Although most bus manufacturer is adding a fully electric single-deck bus to their portfolio, the electrification of a DD bus is a significantly more challenging technological problem. Typically, manufacturers use the empty space on top of the bus roof structure to carry the required batteries but this solution is not an option in the case of a DD bus because of height and centre of gravity restrictions. The batteries therefore need to be packaged within the bus's structure. Optimising and lightweighting the structure would have a direct influence on the amount of batteries required and hence is of critical importance in helping to achieve a fully electric DD bus.

### 3.2.3 ADL's buses: materials and construction

At a fundamental level, ADL buses can be classed as an integrated chassis and semi-monocoque body design. The chassis structure is designed to carry most of the concentrated loadings imposed on the structure by the engine and drivetrain system. The chassis structure needs to be integrated with the bus body frame in order to achieve the required strength and stiffness. The core structural elements of ADL's DD buses are shown in Figure 3.3.

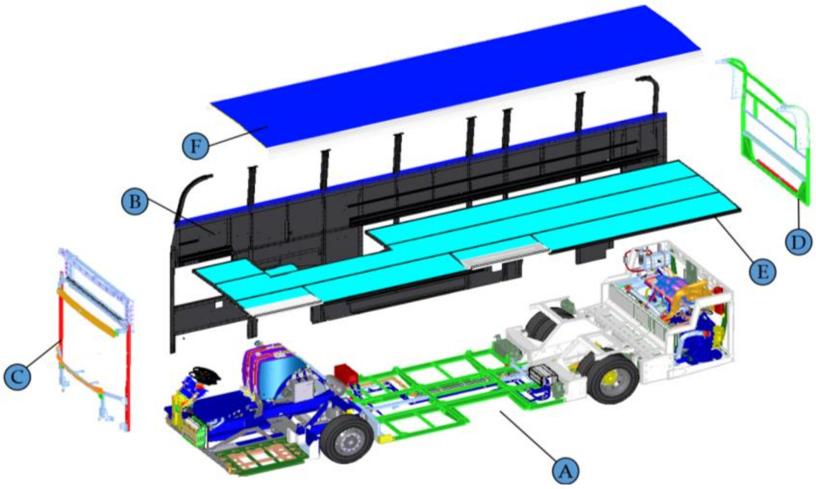


Figure 3.3: Exploded diagram showing the core structural elements of an ADL DD bus. A: chassis, B: body side structures, C: front face structure, D: rear face structure, E: inter deck structure, F: roof structure.

The chassis structure is a 'ladder-type' frame structure. It is divided into three main sections. The front section supports the front axle and driver's pod. The rear section supports the engine and the rear axle/s. The middle chassis structure connects the front and rear section and defines the wheelbase. The three sections are manufactured out of welded closed section steel beams. They are independently manufactured and then bolted together.

The body side-frames consist of a frame built up of mechanically joined aluminium extrusions (6082 T6). Aluminium skins (3103 H14) are then riveted onto the inside of the body frame. The two side frames are mechanically joined (bolted) to the chassis structure. The outside aluminium sheet skins are adhesively bonded to the body frame. The outside skins are not considered as structural elements of the semi-monocoque structure. Sections of the body frame such as parts of the front and rear frames, and the areas around the wheel arches, which are subject to high stresses, consist of a welded stainless-steel frame.

The roof and inter-deck structures are sandwich panel structures whose skins are aluminium 6005A T6 sheets which are adhesively bonded to a closed-cell foam core (extruded polystyrene). The sandwich structure is locally reinforced with the integration of aluminium extrusions wherever localised loading occurs such as at the edges. The main outer beams are termed ‘cantrails’ and are used to mechanically fix the roof and inter-deck structures to the bus body side frames.

The details of the structural materials are presented in Table 1 and illustrated in Figure 3.4.

Table 3.1: Details of main structural materials used on the ADL Enviro buses.

| **Structural element** | | **Section detail** | **Material** |
|---|---|---|---|
| Chassis structure | 1 | Front / rear / middle | Low-carbon steel S355 |
| Body frames | 2 | Front and rear frames | Low-carbon steel S355 |
| Body side structures | 3 | Side frame | Aluminium – 6082 T6 |
| | 4 | Skins | Aluminium – 3103 H14 |
| | 5 | Wheel arches | Low-carbon steel S355 |
| Roof structure and inter-deck structure | 6, 9 | Cantrail + side-edge profile | Aluminium – 6082 T6 |
| | 7, 10 | Sandwich skins | Aluminium – 6005A T6 |
| | 8,11 | Sandwich core | Extruded polystyrene HD300 |

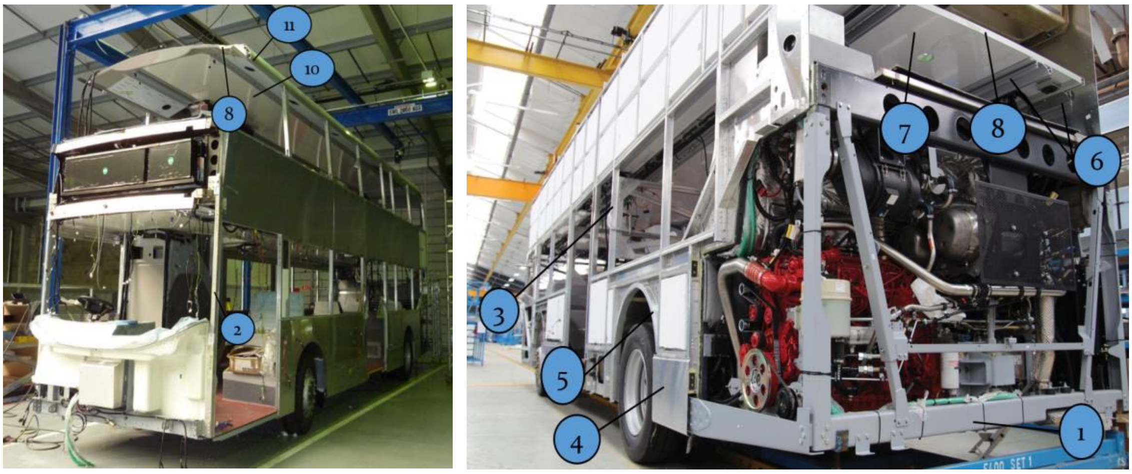


Figure 3.4: Major structural elements of the Enviro400. Details of labelled structures presented in Table 3.1.

Besides evaluating the structural elements and materials, a schedule of the weights of the different structural elements and major systems was built up by extracting the relevant weight from the CAD models as this data was not readily available within ADL. This analysis was carried out to enable assessment of the relative impact of any lightweighting project. This representation was also important in order to differentiate and highlight the components making up the bus structure over which ADL has direct control.

The data was organised utilising Sankey diagrams. An example of one such diagrams produced throughout this research detailing the weight breakdown for a Euro6 diesel Enviro400 DD bus is shown in Figure 3.5. The diagram highlights, that out of a kerb weight of 11,000 kg, around 4150 kg (equivalent to 37%) is primary bus structure, which is under ADL's direct design control (coloured in dark blue in Figure 3.5).

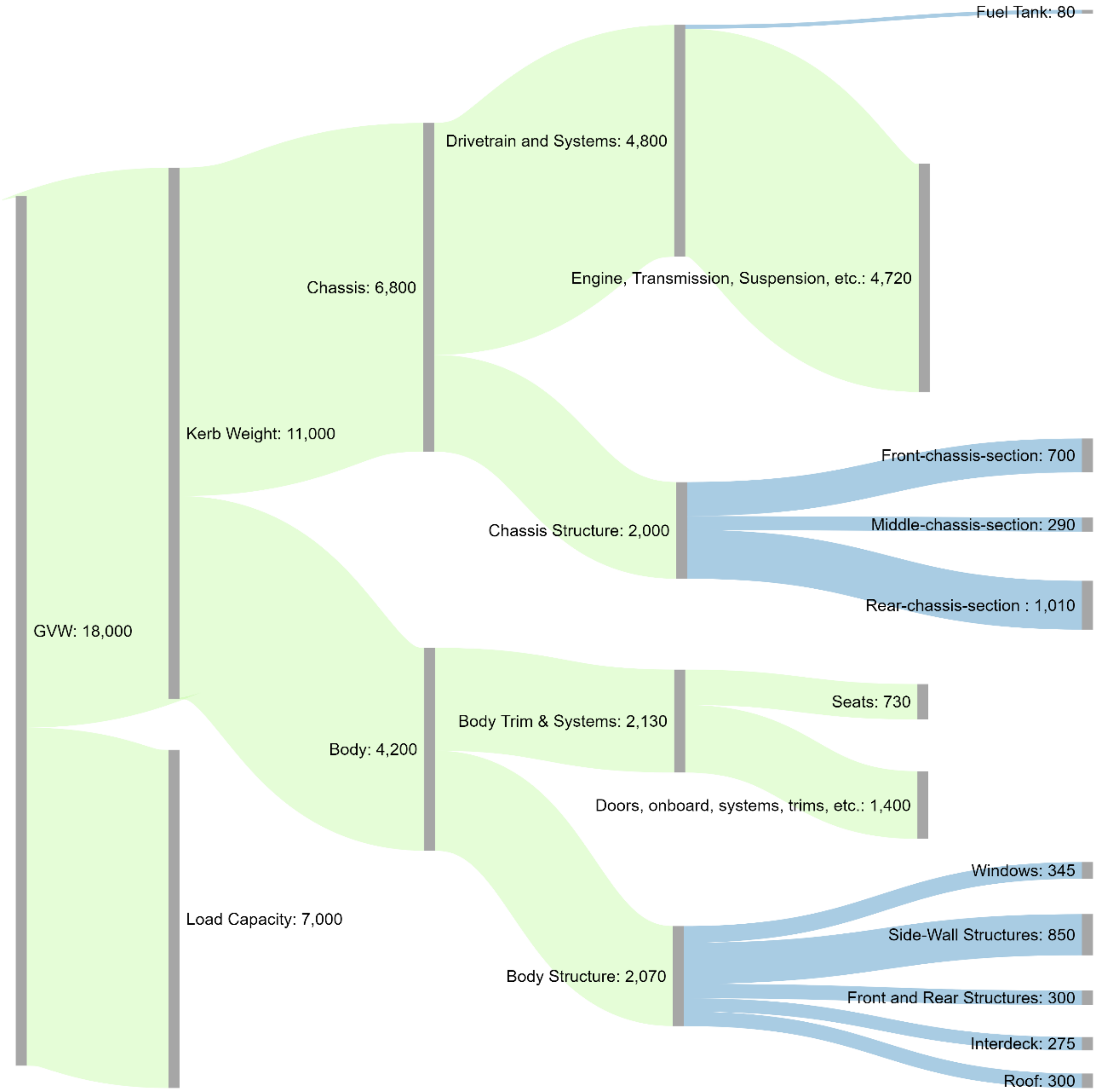


Figure 3.5: Sankey diagram of bus gross vehicle weight distribution. Data based on a 2015 Euro IV diesel Enviro400 DD bus. ADL has direct design control over 37% of the total kerb weight. All weights in kg.

### 3.2.4 Lightweighting within ADL

Following the state-of-the-art review on bus lightweighting technology and the study on the current structures, materials and weights of ADL buses, the final element of information that was necessary to enable the shortlisting of possible lightweighting opportunities was that of lightweighting projects which were being undertaken by ADL (during the initial phase of this EngD).

In 2015, ADL embarked on a major company-wide bus lightweighting exercise intended to achieve 3.5% (400 kg) lightweighting of the Enviro400 DD. The aim was to enable the lowering of $CO_2$ emissions to achieve *Low Carbon Emissions Bus* status which entitled operators within the UK to fuel subsidies [2]. ADL ran a company-wide brainstorming exercise following which all the suggested lightweighting opportunities were sorted and weighted in order of lightweighting potential, cost and difficulty to implement. This lightweighting exercise, supported by the author, was successful in achieving the set target as detailed in Submission #2, with the following being the most significant implemented lightweighting projects:

- **Lightweight components:** The utilisation of lightweight versions of standard systems brought in from tier 1 suppliers such as seats, drive axles and aluminium wheel rims were authorised for this project.
- **Optimisation/reduction of material thickness:** Through a combination of increased CAE capability and the engagement of expert consultancy, various lightweighting opportunities were identified.
    - Reduction of passenger window toughened glass glazing thickness from 4 mm down to 3.2 mm (25% increase in cost due to increased manufacturing costs).
    - Increased manufacturing quality control on GRP moulded parts by utilising closed double sided moulds to ensure accurate wall thickness of components.
    - Reduction of the outside non-structural aluminium skin thickness from 1.6 mm to 1.2 mm.
    - Advanced composite flooring material allowing for a reduction in thickness and weight when compared to the existing plywood flooring.
    - 7% weight reduction of the chassis structure was achieved through an extensive beam section, gauge and shape optimisation process.

## 3.3 Initial feasibility studies on identified lightweighting opportunities

The state-of-the-art review, analysis of ADL bus structures and ongoing lightweighting projects yielded a list of lightweighting opportunities. In order to be able to effectively organise and evaluate all the lightweighting opportunities that were being identified during this stage of the project, a mind mapping software application (MindManager [103]) was used. The tool provided an effective method of organising all the information, which was being collected about the different opportunities, in order to aid with feasibility evaluation. A visualisation of the mind map organising lightweighting opportunities of the Enviro400 DD bus is shown in Figure 3.6.

For any lightweighting opportunity to be considered and investigated further during this EngD, it needed to satisfy the following key elements:

1. Should not be a lightweighting opportunity which ADL is actively investigating as was scoped at the beginning of this EngD by ADL.
2. Should not be a project for which a clearly defined engineering solution is readily available (e.g. lightweighting of a structure by optimisation of beam thickness and profile).
3. ADL manufacturing capabilities as well as cost feasibility have to be considered from an early stage.

As was introduced in section 3.1, this process of lightweight opportunity identification and initial feasibility studies is a cyclic iterative process which is necessary in order to ensure that the right creative innovative solution is identified and taken forward for further development. The rest of this chapter provides a brief overview of the primary lightweighting opportunities that were investigated. These include investigations of lightweight handrails, glazing, fuel tank systems as well as a conceptual design of the middle chassis structure. Finally these studies led to the identification and successful proposal of a project to ADL. This project was taken forward for further development during later stage of this EngD.

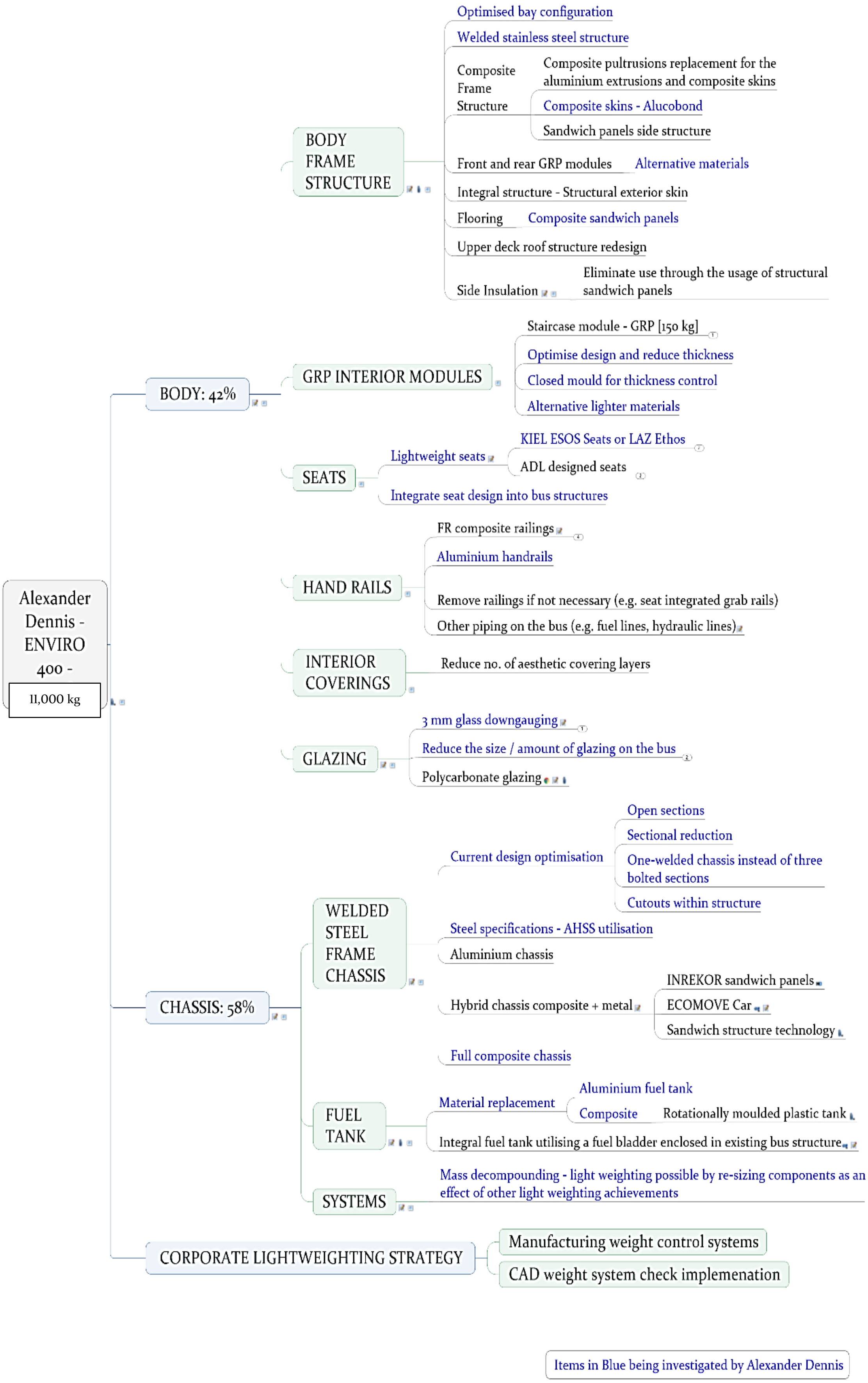


Figure 3.6: Schedule of potential lightweighting opportunities.

### 3.3.1 Lightweight fuel tank

The fuel tank installed by ADL on the Enviro400 DD bus up to 2014 was a welded steel tank with a total capacity of between 250 litre and 350 litre and an average weight of around 80 kg. The tank is typically located under the staircase of DD buses and has a shape as shown in Figure 3.7. During the lightweighting programme detailed in 3.2.4, the fuel tank's weight was successfully reduced to 30 kg by changing to a welded aluminium tank. Two other lightweighting opportunities which could achieve further lightweighting were identified and investigated; a roto-moulded polymer tank and a bladder-type tank.

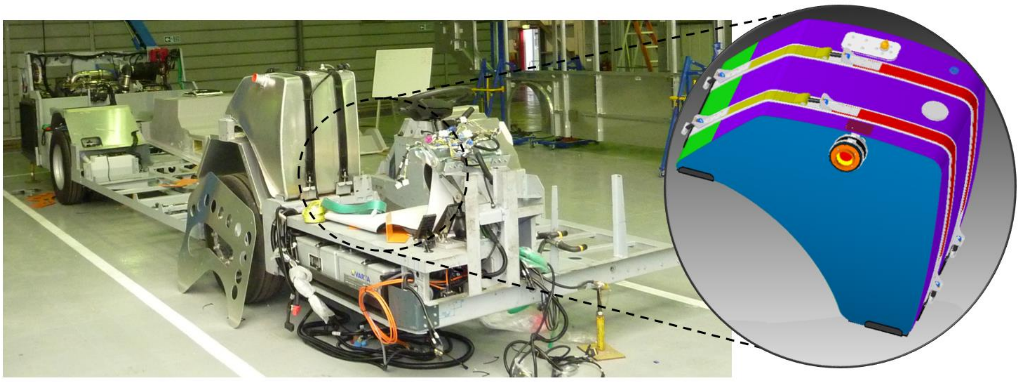
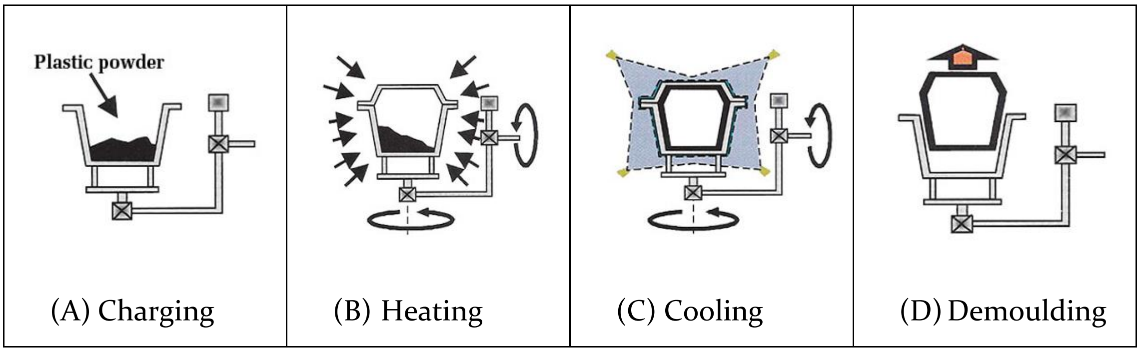


Figure 3.7: Typical fuel tank installed on ADL DD buses – 250 litres welded steel tank – 90 kg.

A manufacturing technology which is widely used in various industries to manufacture lightweight fuel tanks, is rotation moulding as illustrated in Figure 3.8. The investigation of technical and cost feasibility of this option was carried out in collaboration with world leaders in this technology, ATL Ltd. (ATL) [104]. Initial parametric studies indicated that 30% lightweighting over the aluminium fuel tank solution is technically achievable. However, two barriers were identified which blocked further development of this proposal:

- **Cost:** Compared to the manual welding process of the aluminium tank, the manufacturing process would cost less. However, an increase in both the material and tooling costs (tooling cost estimate - £10,000) is expected. Component cost would be dependent on annual production volumes with ATL indicating that at these low volumes (< 500 units annually) a cost increase is expected.
- **Technical issues:** The polymer fuel tank walls would be less stiff than the aluminium tank in order to maximise the lightweighting potential. This has caused issues in the past with a competitors' bus where body panels were deformed by expanding fuel tanks.



(A) Charging (B) Heating (C) Cooling (D) Demoulding

Figure 3.8: Rotationally moulded fuel tanks, adopted from [105].

Following discussion with ADL, it was concluded that although the lightweighting potential at a component level could be significant and the technical issues could be resolved, it was deemed that the maximum weight saving of 10 kg did not warrant the development investment and possible component cost increase.

The feasibility study carried out with ATL was extended to evaluate the possibility of utilising an advanced lightweight fuel tank option, which would consist of a polymer fuel bladder system such as the ones commonly used in the aerospace and marine industries. ATL indicated that a simple shaped 250 litre bladder would weigh approximately 5 kg. However, these bladders would need to be supported within an enclosure and it would only be feasible to implement this option if this enclosure was defined by other components of the bus structure. Such an enclosure is not currently available on current ADL buses, although a proposed redesign of the middle chassis structure as detailed in section 3.3.3 could present such an opportunity.

### 3.3.2 Lightweight handrail system

Passenger handrails currently consist of mild steel tubes, which are cold-bent into the required shape and powder coated to provide the required surface finish. A typical full set of handrails on a DD bus have a total mass of around 55 kg. Previous investigations by ADL on the feasibility of utilising aluminium handrails concluded it was economically infeasible. Polymer FR composite handrails have been successfully manufactured to replace steel handrails in industries such as off-shore platforms [106] and in the rail industry [107]. These composite handrails were manufactured utilising pultrusion, which is a highly cost-effective manufacturing process. However, this solution is not readily transferable to the bus industry as most handrails have complex curved shapes, which are impossible to manufacture utilising current pultrusion technology. An alternative manufacturing process capable of producing hollow structural composite beam structures with a cost-effective automatic fibre placement process is braiding followed by an adequate fibre-matrix consolidation process. Initial feasibility studies, which were carried out showed that this manufacturing technique could potentially be exploited to not only achieve lightweighting of handrails but also other beam structures present within the bus structure. Further details of this research are presented in chapter 5.

### 3.3.3 Lightweight polymer glazing

Glass is the predominant glazing material on buses. Two types of glass are typically used, either toughened (tempered) safety glass or laminated safety glass. As introduced in section 2.5.4.3, clear solid polymer glazing is being successfully introduced and replacing glass glazing in other industries with up to 60% lightweighting being achieved [108]. An Enviro400 DD bus has more than 300 kg of glass glazing and hence the utilisation of polymer glazing could achieve significant lightweighting.

There are two main polymers that could be useful for glazing applications; Polymethyl methacrylate (PMMA), commonly known as acrylic, and polycarbonate (PC) both of which are transparent thermoplastics [109]. Although acrylic has several advantages over PC (lower cost, higher scratch resistance and resistance to UV exposure), PC has one critical advantage over acrylic and glass, in that it possesses exceptionally high impact strength and is considered to be virtually unbreakable, having up to 200 times the impact strength of glass and 50 times that of acrylic [110]. Legislative bodies around the world are actively proposing that bus glazing systems would be able to prevent the ejection of passengers in case of accidents with such legislation mandating the utilisation of either laminated glass glazing systems or PC glazing [111].

Despite the lightweighting potential and its superior impact resistance, PC glazing has significant deficiencies which need to be addressed, the primary of which being its inherently poor scratch resistance and weatherability [112]. Indeed, earlier failed applications within the auto industry led to a current negative perception of the technology. In order to assess the realistic feasibility of the introduction of PC glazing within the bus industry, a state-of-the-art review was carried out in collaboration with one of the world’s leading polycarbonate suppliers, SABIC Innovative Plastics Holding BV [113]. The following were the key outcomes of the study:

- **Structural stiffness and lightweighting potential:** The current legislation allows the utilisation of thin (4 mm) toughened glass for large and flat side passenger glazing, the lower structural stiffness of PC limits the lightweighting potential. However, if the shape of glazing could be changed to achieve increased panel stiffness through curvature, the required PC panel thickness could be reduced.
- **Abrasion resistance:** Detailed analysis of abrasion resistance of coated PC glazing exposed to industry-specific conditions needed to be analysed.
- **Cost:** Coated PC glazing could cost anywhere from 30% to 300% more than glass [113].

Hence, it was concluded that the direct replacement of flat side toughened glass windows with PC glazing is not economically feasible as the lightweighting potential is limited. However, PC glazing could achieve significant lightweighting at an economically feasible cost penalty when replacing laminated glass in situations where the glazing panel has a curved shape. This opportunity was exploited in the design of the proposed lightweight upper-deck structure presented in chapter 4 and explored in detail in chapter 6.

### 3.3.4 Middle chassis structure

The Enviro400 rolling chassis including all the drivetrain as illustrated in the top section of Figure 3.9, weighs approximately 6,800 kg and accounts for 62% of the bus GVW. The bare chassis structure which is designed by ADL weighs about 2,000 kg. This consists of a ladder-type chassis structure which is the backbone of the whole bus structure. It consists of three separate sections of welded steel tube structures, which are bolted together to form the complete chassis as shown at the lower part of Figure 3.9.

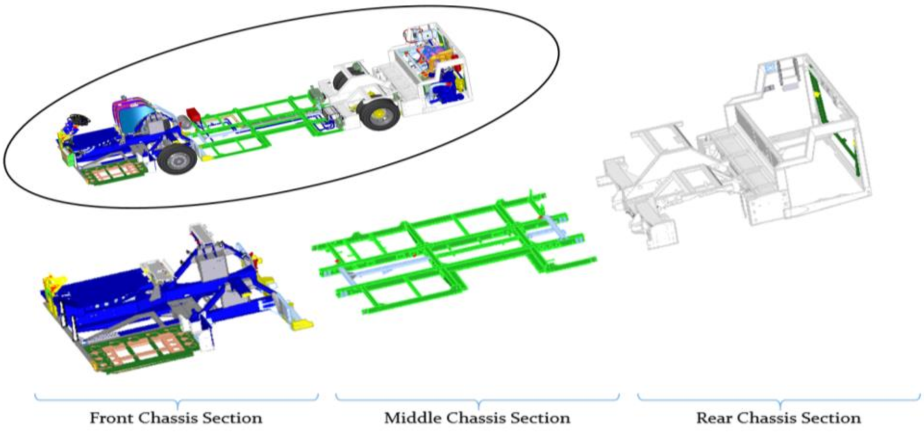


Figure 3.9: The chassis of an Enviro400 DD bus. Top: Full equipped chassis structure and drivetrain (6,800 kg). Bottom: The bare front, middle and rear chassis sections (2,000 kg).

Out of the three sections of the chassis structure, the middle chassis section is a relatively flat and geometrically-simple structure. Taking inspiration from the success of the ADL's lightweighting of the bus inter-deck structure by replacing the metal frame with a sandwich panel-type structure, a project to investigate the feasibility of carrying over this concept to the middle-chassis structure was investigated. Initial CAD modelling of the concept, which consisted of an aluminium skin and closed-cell foam core with localised reinforcements as illustrated in Figure 3.10, indicated that a 30% lightweighting of the 400 kg structure could be achieved. Following these initial design feasibility studies, in order to further assess the viability of the project, various specialist manufacturers of sandwich structures including 3A Composites GmbH (3A) [114] and Stewart Morley, inventor of the Inrekor™ system [115], were engaged. 3A were contacted as they were supplying ADL with the inter-deck sandwich structure. Following initial discussions, new with the author, 3A carried out further detailed design of the proposed concept and presented separately to ADL a commercial proposition for the supply of a lightweight middle chassis structure based on the concept identified in this EngD research.

Inrekor™ is a structural system consisting of mechanically and adhesive joined sandwich panels (aluminium sheet skins with an expanded polypropylene foam core, ARPRO™) which has been successfully utilised to manufacture vehicle chassis prototypes as illustrated in Figure 3.10. Compared to the original concept of having a solid sandwich structure as originally designed and eventually proposed to ADL by 3A, this system would retain a working volume within the core of the chassis design space which could be utilised to house systems or even a lightweight fuel bladder.

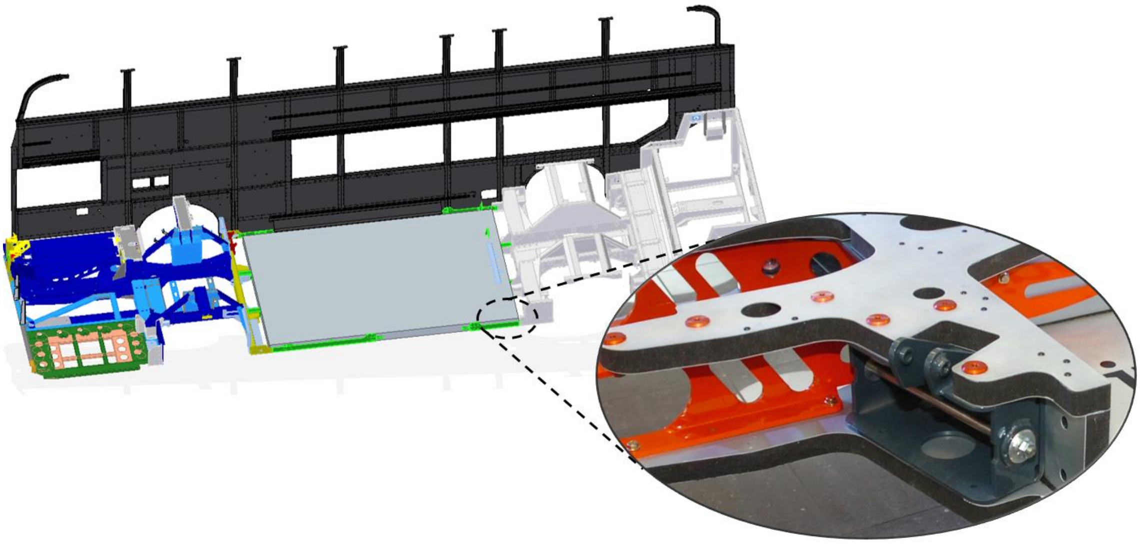


Figure 3.10: Proposal for lightweight middle-chassis structure: The feasibility of utilising a sandwich-panel based box structure based on the Inrekor™ system was evaluated, adopted from [115].

However, neither the commercial proposal by 3A nor the proposal presented in collaboration with Inrekor™ for the development of lightweight middle chassis structure were taken further by ADL. ADL indicated that the absolute weight saving of approximately 120 kg resulting from the 30% lightweighting of the middle chassis structure was not radical enough to justify the significant risk associated with the project. ADL indicated that the project proposals illustrated the significant lightweighting potential and commissioned specialist composite manufacturer Gurit(UK) Ltd [116] to investigate the feasibility of a full composite chassis structure. This six month design project, whose evaluation was assisted by the author, illustrated that 40% lightweighting of the whole chassis structure could be achieved. However, ADL did not extend investment on this project based on three critical issues, which the project highlighted:

- **Cost:** Gurit indicated that a composite chassis would have a direct cost penalty over the steel chassis of £16/kg of lightweighting. As indicated in section 2.4.3, this investment in lightweighting could be recovered during a bus lifetime. However, ADL expect the cost to be significantly higher than indicated by Gurit particularly because of the extensive testing and validation programme that would be necessary for ADL to shift to this new technology platform.
- **Perceived customer acceptance:** ADL perceive high reluctance from the bus operators to invest in this technology particularly as information on in-service reparability and lifetime performance is very limited.
- **Technical challenges:** Finally, it was concluded that it would not be possible to implement this project in isolation. A redesign and lightweighting of the body frame structure would also be necessary as the significant weight reduction of one of the bus lowest structures would result in a higher centre of gravity (COG), which could possibly result in the bus not passing the legally required tilt-test.

### 3.3.5 Bus and upper-deck structure

The final significant feasibility study focussed on the body frame structure. Initial lightweighting feasibility studies of the body side-structures did not yield any realistic or significant lightweighting potential. However, whilst evaluating the possibility of adapting the technology developed during the EU funded LITEBUS project presented in section 2.5.4.2, a novel lightweight redesign of the upper-deck structure was conceived.

For the scope of this EngD research, the term ‘upper-deck structure’ refers to all the elements above the horizontal beam running the whole length of the bus at the bottom of the windows of the upper-deck, typically called the ‘waist rail beam’ as illustrated in Figure 3.11. Within ADL, this structure is typically referred as being a ‘big umbrella’ because it is not considered to be a structure onto which the structural integrity of the rest of the bus structure is dependent although it affects the COG of the whole vehicle detrimentally. In fact, there is an open top-deck version of the Enviro400 bus which is offered to the touristic sight-seeing market, and the side-frames and chassis structures are identical to the standard bus with no additional reinforcements needed. This structure consists of a sandwich panel roof assembly which is supported by vertical aluminium extrusion beams. The windows consist of glass panels which are mounted within aluminium frames. The weight of this structure on the Enviro400 is in excess of 500 kg. The main mechanical performance requirements are primarily limited to self-support and unlike most of the other major structures making up the bus, the upper-deck enclosure does not need to support any major loads such as drivetrain or passenger loadings. On further analysis, it was evident that the assembly is very similar to the roof assembly of a single-deck bus and it is likely the case that the design of the upper-deck structure was translated from the single-deck bus structure as opposed to a design specific to the upper-deck structure. A blank sheet design approach was adopted in order to evaluate if a design specifically for the upper-deck of a DD bus could achieve significant lightweighting. A comparison of the upper-deck roof structure’s weight (500 kg) with that of the weight of the structurally-critical body side-frame structures (850 kg) further highlighted the potential of feasible lightweighting of the upper-deck structure.

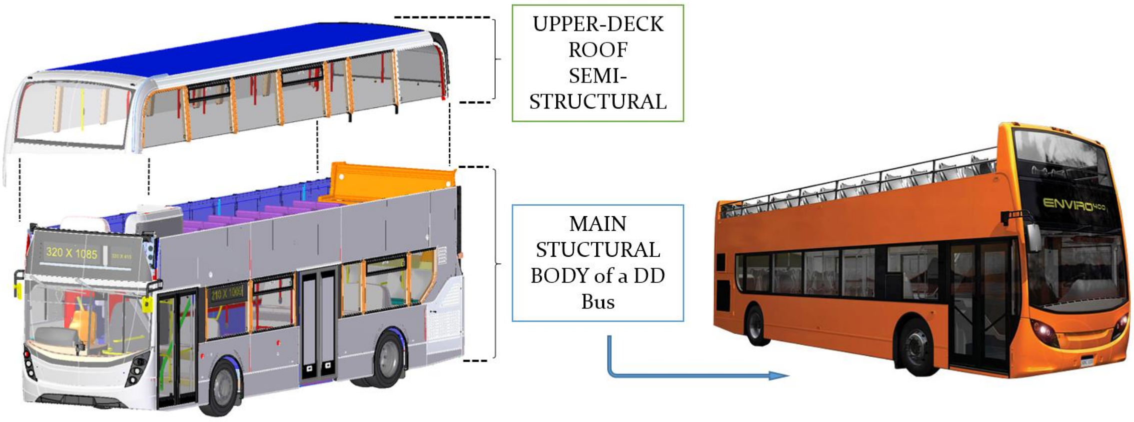


Figure 3.11: Left: Definition of the upper-deck roof structure. Right: The Enviro400 open-top bus requires no additional reinforcement of the main structural body following the removal of the upper-deck roof structure.

A proposed lightweight redesigned upper-deck structure concept is illustrated in Figure 3.12. The proposed design seeks to transform the cross-section of the structure from a rectangular form to a structurally-more-efficient dome structure. Curved structural beams support a roof sandwich panel of reduced width, whilst curved polycarbonate glazing panels could be efficiently utilised to finalise the proposed structure. Initial weight estimates indicated that 40% weight reduction of the structure could be achieved. The concept was proposed to ADL, who agreed that the radical redesign required further detailed design in order to confirm its viability particularly its compliance with cabin volume legislation and packaging of systems.

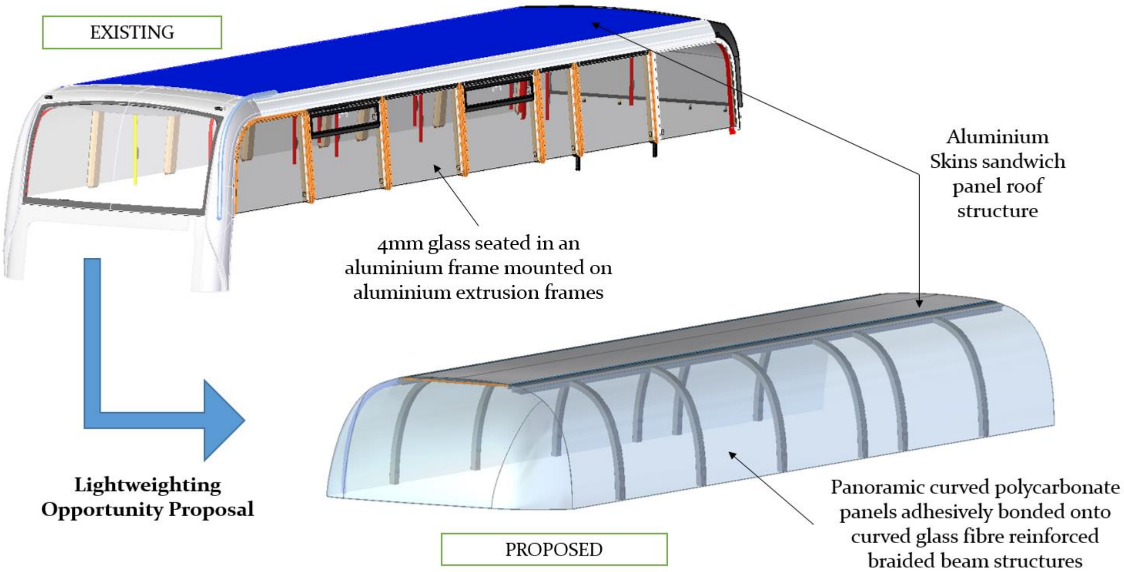


Figure 3.12: The lightweight panoramic roof concept proposal.

## 3.4 Review of lightweighting feasibility studies

It could be concluded that the research methodology adopted by the author and sponsor company successfully led to the identification of a high impact novel lightweighting opportunity. The proposed lightweight upper-deck structure concept was neither directly identified in the literature nor was it suggested by ADL. Information from the state-of-the-art review, the systematic analysis of ADL bus structures and the various feasibility studies led to the evolution of the concept. Initial lightweighting feasibility studies consisted of single component analysis such as handrail tubes, the fuel tank and glazing panels. The common conclusion was that although technically feasible lightweight solutions were identified, their implementation came with a cost penalty which was not considered acceptable. Throughout this process, it became evident that for a successful lightweighting opportunity to be identified, it was necessary to evaluate a whole system. The various studies finally culminated into the conception of the novel lightweight upper-deck roof structure. ADL confirmed that the upper-deck structure proposal was to be taken forward by the author for further feasibility investigation and development. This decision was based on these main factors:

- The project had the potential of delivering significant lightweighting potential.
- Its successful implementation would enable future lightweighting projects; the structure being considered will have a significant effect on the centre of gravity of the bus, which could in turn enable lightweighting of lower-height structures such as the chassis.
- The structure being considered is not a ‘primary’ structure, hence offers an ideal opportunity for ADL to introduce novel systems to the market with reduced risk.
- The structure has a smaller frontal area and is expected to have a better coefficient of air-drag than the current structure, hence would reduce energy consumption of the bus as a result of reduced aerodynamic drag (this benefit is only significant on bus routes having higher than average speeds).
- Key component technologies such as polycarbonate glazing and braided FR beam structures could be applied to other areas of the bus.

During the project proposal review, ADL indicated that in order for the project to progress, further detailed design was necessary to demonstrate that the proposed upper-deck design is compliant with any relevant design regulations such as minimum cabin volume and passenger headspace requirements. Chapter 4 will present the detailed design that was carried out to confirm the viability of the proposed structure.

# 4

# DESIGN OF A NOVEL LIGHTWEIGHT UPPER-DECK STRUCTURE OF A DD BUS

This chapter presents the detailed design development of the lightweight upper-deck structure concept introduced in chapter 3. Following the initial feasibility study and concept proposal to ADL, it was concluded that a detailed design was necessary to confirm compliance of the conceptual structure with any relevant cabin interior volume legislation and that any necessary systems such as the air-conditioning (A/C) ducting could be integrated within the structure. ADL also indicated that the design development should be based on the Enviro500 as this model is equipped with cabin air-conditioning system, hence providing a worst-case scenario for the design viability verification of the conceptual structure.

Details of the current upper-deck structure including a review of the loadings imposed on the structure and relevant design legislation are presented. The design process that was followed to model the proposed lightweight upper-deck structure is then detailed. Following a project benefit assessment, a high-level risk analysis of the proposed structure is presented detailing critical aspects of the project. This risk assessment will hence dictate what further investigation is necessary to increase the degree of confidence in the overall feasibility of the proposed lightweight upper-deck structure.

## 4.1 The Enviro500 DD bus and current upper-deck structure

The ADL Enviro500, illustrated in Figure 4.1, is their largest low floor entry, 3-axle DD bus. Its additional axle compared to the Enviro400 allows increase in the GVW to 26,500 kg hence offering a total capacity of up to 146 passengers out of which 98 can be seated [117]. The Enviro500 is the world's best-selling DD bus [118] and is strategically a very important model in ADL's line-up as it offers the company the best possibility of expansion through export to new markets.

Figure 4.1: ADL Enviro500: 13 m long, 3-axle bus with 26,500 kg GVW, reproduced from [117].

As mentioned in chapter 3, for the scope of this EngD research, the term 'upper-deck structure' refers to all the elements above (but not including) the horizontal beam running the whole length of the bus at the bottom of the windows of the upper-deck, typically called the 'upper-waist-rail beam' as defined in Figure 4.2.

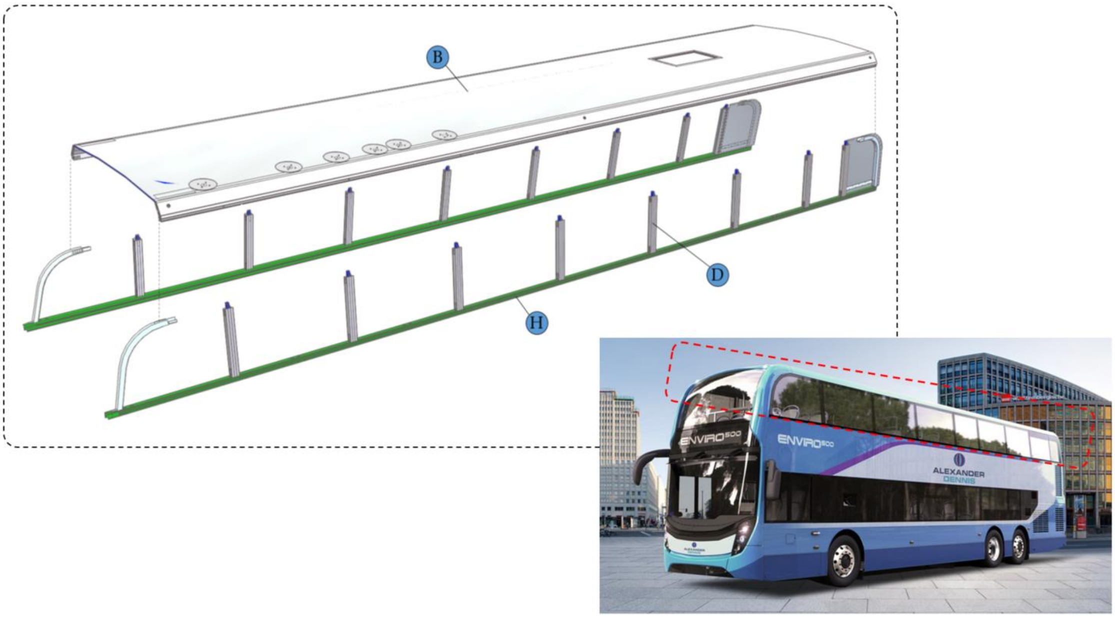


Figure 4.2: An exploded view of the main structural elements of the upper-deck structure. Vertical pillars (D) are joined to the waist-rail beam (H). The roof panel (B) is then mechanically joined to the vertical pillars. The waist-rail beam is not considered part of the upper-deck structure in this research project.

The main structural elements of the upper-deck roof structure are a series of vertical pillars which support the roof sandwich panel. The vertical support pillars are made of straight aluminium extrusions (6082 T6 aluminium alloy). The roof panel is a sandwich panel structure consisting of 1.2 mm aluminium skins (3103 H14 aluminium alloy) adhesively bonded onto a 13.4 mm thick extruded polystyrene core. Two aluminium extrusion beams (cantrails) are embedded on the two running longitudinal edges of the sandwich panel in order to enable the roof panel to be joined to the vertical pillars and also support the glazing. All the glazing on the bus is glass which is either adhesively bonded directly onto the bus frame structure or in the case of the emergency exit designated panels, mounted within openable extruded aluminium frames.

The total weight of the Enviro500 upper-deck structure is in excess of 700 kg depending on the exact configuration as specified by the bus operator. The weight of the main common elements of the upper-deck structure that were considered for this study are the following:

| | |
|---|---|
| Vertical pillars | 34 kg |
| Roof sandwich structure | 301 kg |
| Glazing system | 275 kg |
| **Total primary structure weight** | **610 kg** |

### 4.1.1 Structural strength and stiffness requirements

It is important to note that the upper-deck structure is not an integral part of the main bus structure, i.e. it could be effectively removed from the bus and the remaining structure would still possess the required strength and stiffness for the bus operation as was introduced in section 3.3.5. The structure therefore needs to be self-sustainable when exposed to dynamic in-service loads. Additionally, the structure needs to resist particular loading conditions such as snow loading, side-wind loading or the condition of a person standing on the roof defined as 1300 N imposed on an area of 100 mm x 300 mm. These loading conditions and structural performance requirements are set by ADL, however the structure needs to comply with the relevant legislation as summarised in the next section.

### 4.1.2 Review of relevant legislation

Following are the aspects of legislation with a direct influence on the redesign process:

- **Structural strength requirements:** The two main relevant design regulations are *UN-ECE addendum 106, regulations no. 107* (R107) [119], and addendum 65, regulation no. 66 (R66) [120]. Between them, these regulations define and constrain most aspects of bus design such as the strength requirements of the bus superstructure and other design elements such as doors, windows, gangways, seats, handrails, lighting, etc. R66 was introduced to ensure that large passenger vehicles have adequate structural strength to protect passengers in case of a roll-over type accident. Currently DD buses do not have to comply with R66 hence it is up to the manufacturer to ensure that the strength of a DD bus superstructure is suitable for its intended purpose.
- **Design space requirements:** One of the most important legislative aspects for the design of the upper-deck is paragraph 7.7.8.6 of R107 which defines the free height over a seating position. These effectively constrain the design space envelope for the structure as will be detailed in section 4.2.
- **Tilt-test:** Paragraph 7.4 of R107 defines that a bus needs to avoid overturning when it stands on a surface which is tilted to $28^{o}$. During the test, every single seat on the top-deck must be loaded with a weight equivalent to a standard passenger (75 kg) whilst the lower-deck must be empty except for the driver's weight [121]. The upper-deck structure has a very significant effect on the bus centre of gravity location and its weight could determine whether a DD bus complies with this test as will be detailed in section 4.4.
- **Roll-over and passenger ejection protection**: Following the introduction of the R66 regulation which ensured that the roof structure of single-deck buses had significant strength in order to avoid collapse and subsequent crushing of passengers, the severity of bus rollovers has been significantly reduced. However, the ejection of passengers has now become the second most dangerous injury mechanism [122]. Following a recent accident within the rail industry, which involved the overturning of a tram in Croydon, UK, it was concluded that the ejection of passengers from the cabin through broken toughened glass was the main reason for the fatalities that occurred [123]. In 2016, the US National Highway Traffic Safety Administration (NHTSA) proposed a new Federal Motor Vehicle Safety Standard (FMVSS) No. 217a, 'Anti-ejection glazing for bus

portals' [111]. This would necessitate the utilisation of advanced glazing systems that would be able to resist` the load imposed by a person impacting the window at a bus rollover situation. If this legislation comes into force, the only feasible glazing options would be laminated glass or PC. When compared to laminated glass, PC would offer a cost feasible and significantly lighter option and could become the predominant glazing material within the bus industry.

## 4.2 Design details of the proposed upper-deck structure

As was introduced in section 3.3.5, the initial design inspiration for the proposed concept was that of converting the rectangular roof shape into an engineering efficient dome-type structure as illustrated in Figure 4.3. As will be detailed, this geometrical holistic redesign of the structure is the key enabler of the significant weight reduction that is achieved.

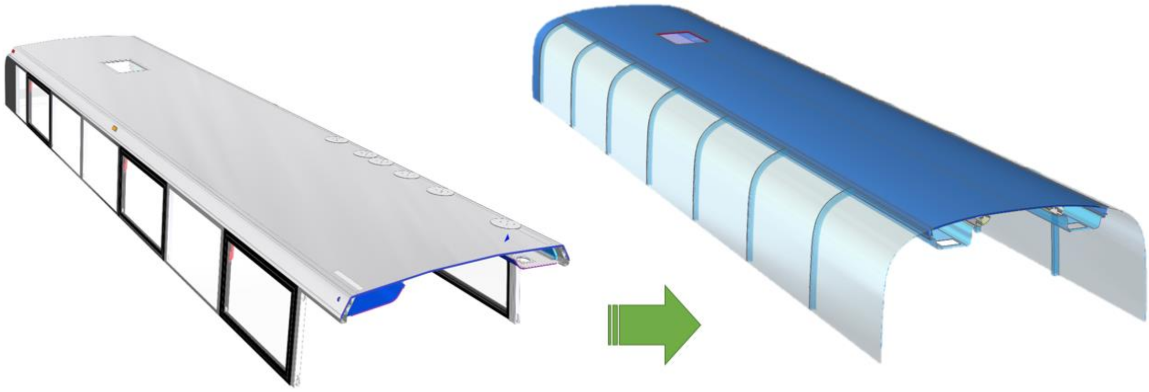


Figure 4.3: Current upper-deck structure (left) and the proposed lightweight structure (right).

### 4.2.1 Lightweight upper-deck structure design philosophy

The first stage of this design process consisted of defining the design envelope in which the proposed structure must fit in order for it to be compliant with relevant legislation. Following the definition of this design space within the CAD model, the shape of the structure was defined as detailed below:

- The shape-definition of the curved beams was constrained to have the curvature with the maximum radius possible within the constrained design space which is defined by

R107 as illustrated in Figure 4.4. Avoiding a tight radius of curvature was necessary to ensure cost-effective manufacturability of both the curved beams and glazing panels.

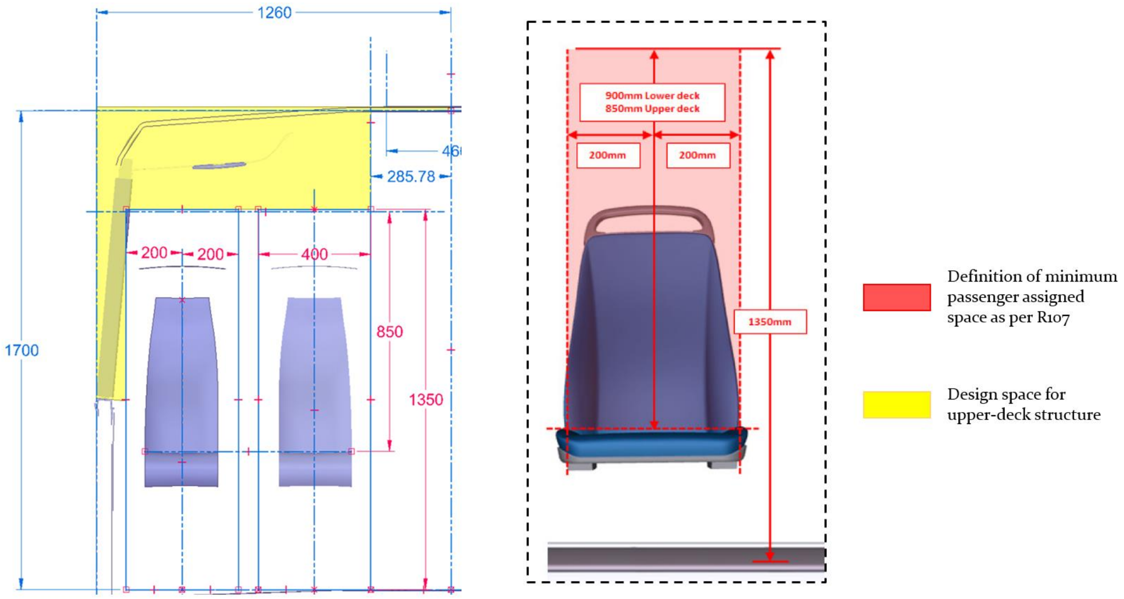


Figure 4.4: Definition of the design space of the upper-deck roof structure as defined by R107 [119].

- Analysis of the current cantrail beam indicated that one of the key reasons behind the size and hence weight, is a geometric requirement rather than specific strength and stiffness requirements. The cantrail beam spans the height from the top of the window sills to the top-level of the roof panel. The proposed design allows the curved beams to be extended up to the roof top level hence both the span of the roof sandwich panel as well as the cantrail beam cross-section could be reduced as illustrated in Figure 4.5.

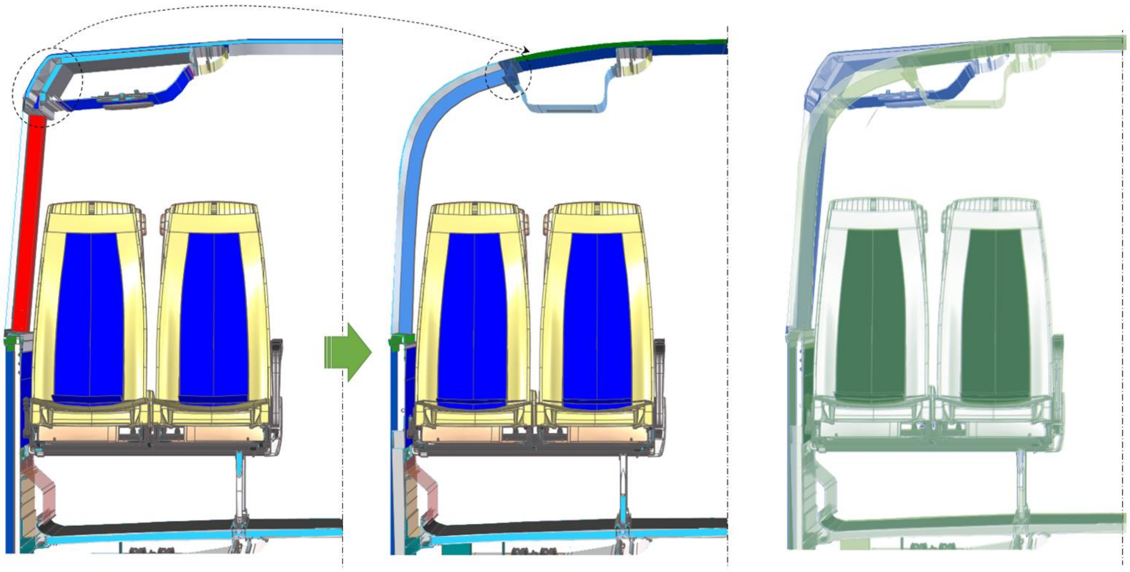


Figure 4.5: Left to right: Schematic of the current structure, the proposed upper-deck structure and a superposition of the two.

- Following the definition of the primary structural elements, the second stage of this design phase involved the redesign of the A/C ducting, lighting and other systems to ensure they could be accommodated by the new design. The A/C ducting and lighting systems were moved towards the central corridor of the bus by 250 mm, but still they do not encroach onto the middle walking corridor and hence the design is fully conformant with relevant legislation as illustrated in Figure 4.6.

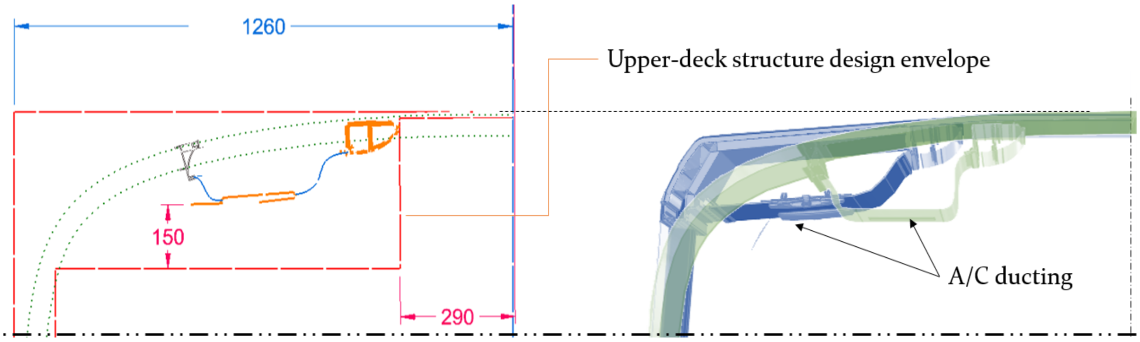


Figure 4.6: Superposition of the proposed structure (green) over the current structure (blue). The diagram on the left illustrates how the proposed structure fits within the allowable design space as defined by R107.

A 3D projection of the resultant proposed structure is illustrated in Figure 4.7.

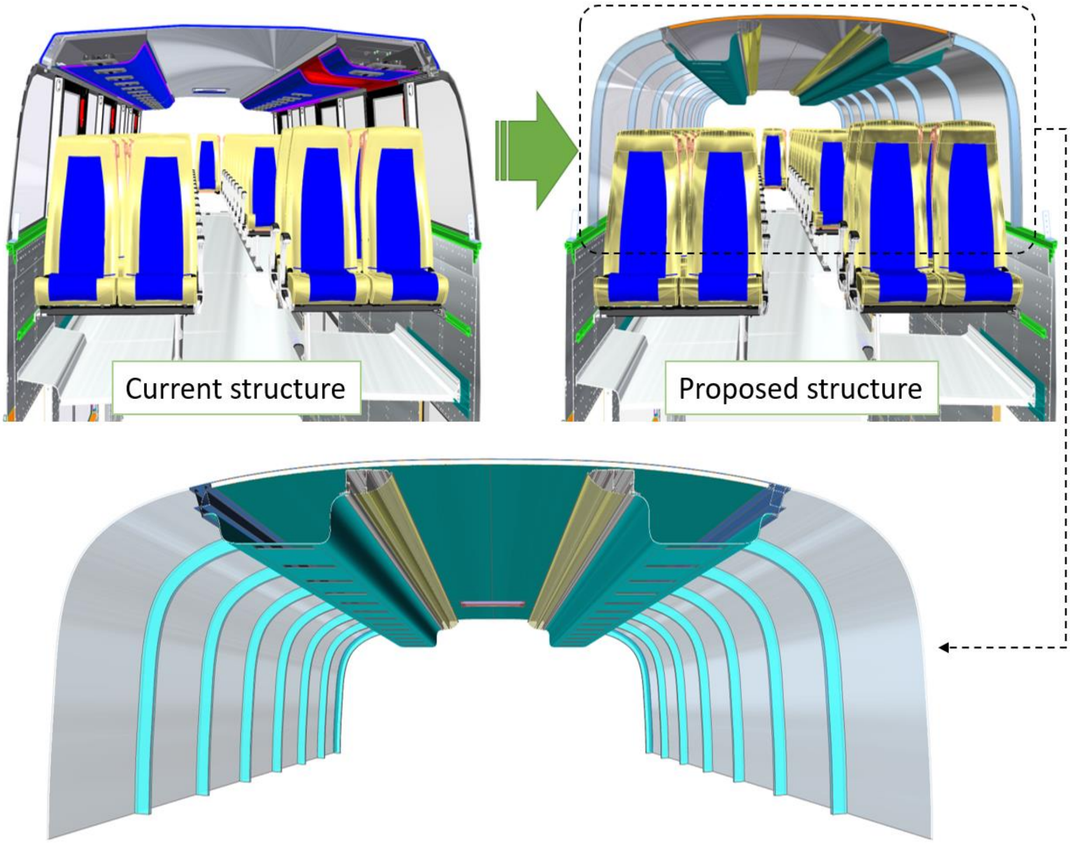


Figure 4.7: 3D projection of the interior of the proposed upper-deck structure.

## 4.2.2 Main structural elements of the proposed upper-deck structure

The main structural elements of the proposed structure are the curved vertical beams, glazing panels and the sandwich-type roof panel as illustrated in Figure 4.8. This section discusses the details of the materials and manufacturing methods that could be utilised to realise the structure.

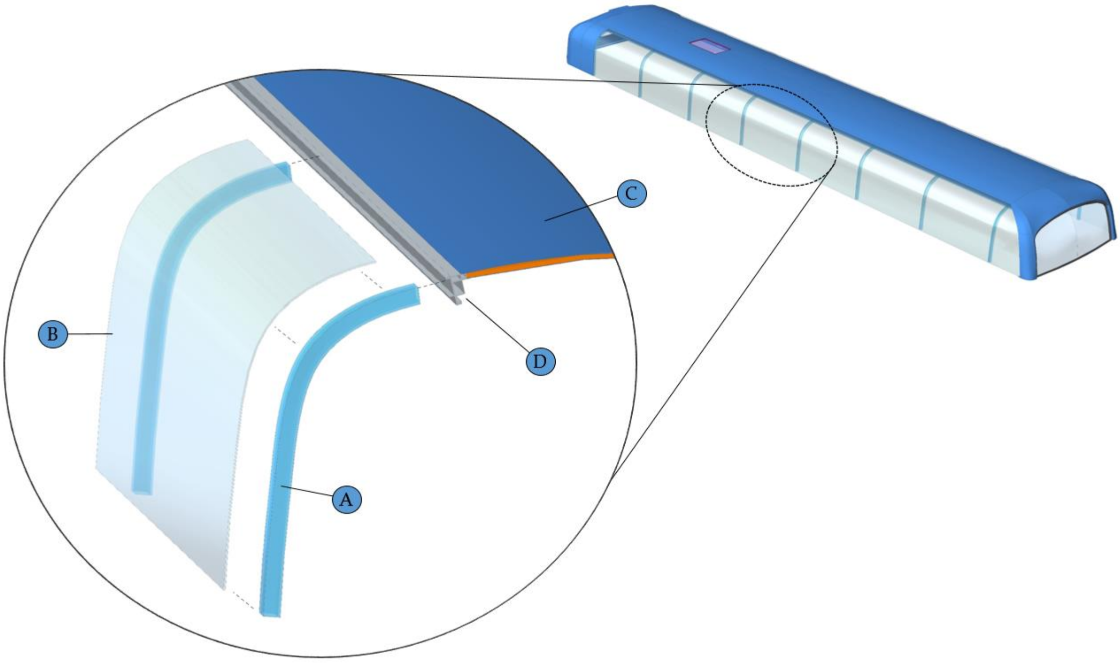


Figure 4.8: An exploded view of the proposed structure. Curved beams (A) support a sandwich panel roof structure (C) which incorporates the cantrail aluminium extrusion beams (D). This structure would support panoramic curved glazing panels (B).

**1. Sandwich panel roof structure:** The existing roof structure consists of a sandwich-type structure as defined in Table 3.1. Previously, the roof structure consisted of an aluminium skin adhesively bonded onto an aluminium extrusion frame assembly. ADL confirmed that the current structure is lighter than the previous structure and enabled a faster final assembly onto the bus body. Hence, the same lightweight roof construction was integrated into the proposed upper-deck redesign. At this first design iteration, the weight estimate of the roof structure was based on retaining the same materials and thicknesses as the current design. However, given that the free spanning width of the roof is reduced by a third as a direct consequence of the redesign, there is opportunity for a lightweighting optimisation of the thickness of the sandwich structure, which could be carried out at later design iterations.

**2. Curved structural beams:** The roof panel is proposed to be supported by structural curved beams. Two options were shortlisted as suitable lightweight candidates for these beam structures:

- Aluminium extrusions which are subsequently bent. Aluminium extruded beams are at the core of the bus body frame structure but all of these structures currently utilised by ADL are straight. Although the bending of aluminium extrusions is far from being a trivial manufacturing operation, there are specialist companies who have the capabilities of manufacturing such beams [124, 125].
- Fibre-reinforced braided beam structures. ADL expressed interest in investigating this novel technology. A work package, was carried out to investigate the feasibility of utilising braided FR composite beam structure for lightweight handrails demonstrated that the technique could be utilised to manufacture these curved beams as will be detailed in chapter 5.

**3. Curved glazing panels:** The final key component to the structure is the set of curved glazing panels. Taking into consideration safety regulations regarding the prevention of ejection of passengers in emergency situations, the glazing panels would have to be manufactured using either laminated glass or polycarbonate. The curved shape of the panels provide the ideal case for polycarbonate glazing to be utilised in order to maximise the lightweighting potential of the design.

## 4.3 Analysis of lightweighting potential

The CAD model of the proposed structure was utilised in order to obtain a weight estimate and evaluate the lightweighting potential of the proposed structure. A conservative weight estimate of the proposed structure indicates a significant weight reduction of approximately 257 kg (42% of the original structure). A comparison of the weight of the major components of the current and proposed structures is shown in Figure 4.9.

The following are the key assumptions on which weight calculations are based:

- Only the weight of the major structural elements is being considered. The weight of joining materials, adhesives and other trims is not included. However, given the similarity in assembly of the current and proposed structures, any change in weight is not expected to be significant.

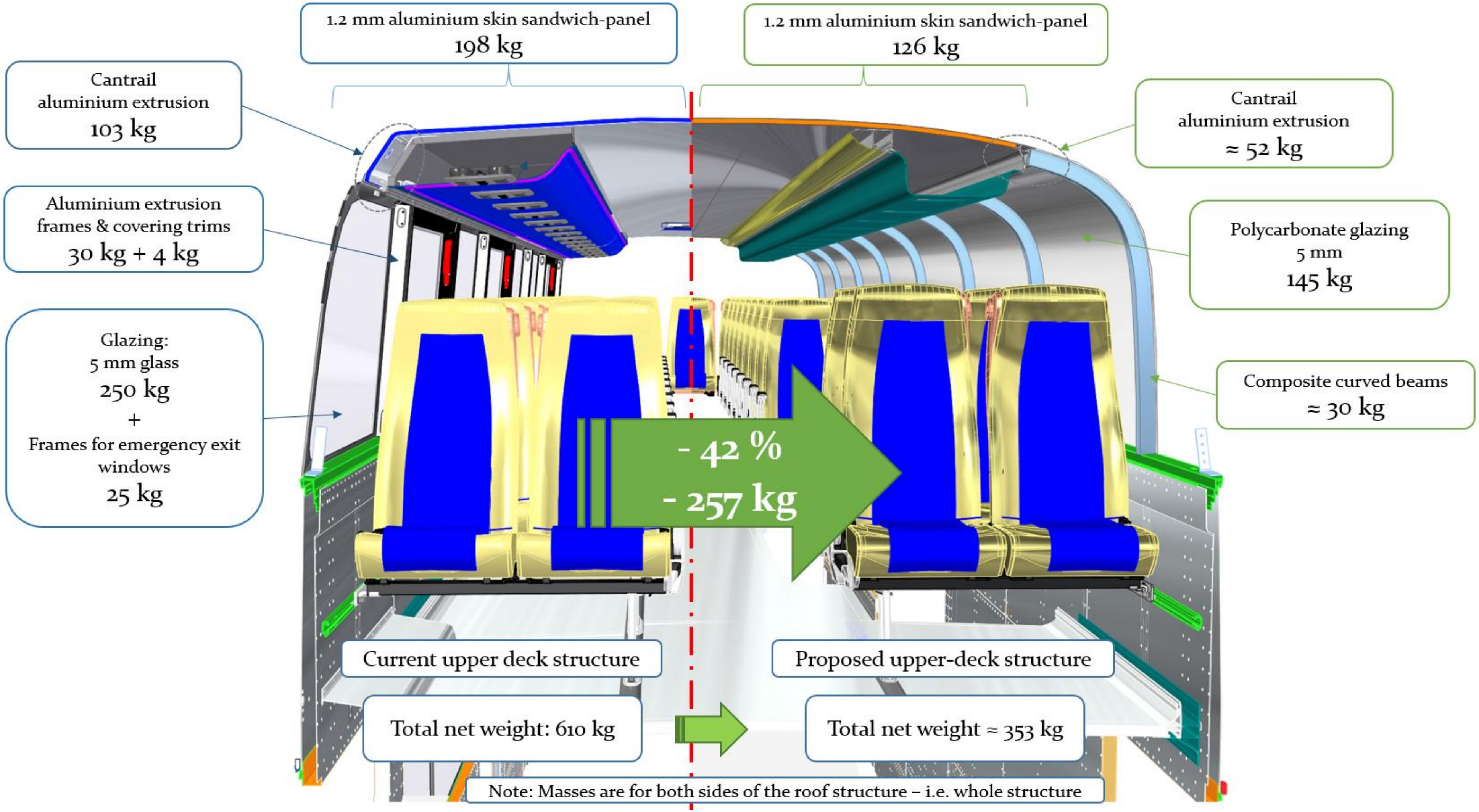


Figure 4.9: Lightweighting potential summary: schematic showing the weight of the primary structural elements of the current structure (left) and the proposed structure (right).

- The weight of the vertical curved beams was empirically calculated using the information acquired during the handrail lightweighting project. It is expected that the proposed conservative beam-wall thickness of 5 mm will provide the necessary structural stiffness.
- The weight of the polycarbonate glazing is significantly dependent on the thickness. Initial feasibility discussions held with Sabic concluded that 4 mm should provide a sufficient level of panel stiffness, however a more conservative 5 mm panel thickness is assumed for these initial weight estimations.
- The weight of roof panel and cantrail are based on retaining identical materials, and same cross-sectional thicknesses as the current structure. Given that the span of the roof panel has been reduced by 30%, design optimisation will likely yield further lightweighting potential.

## 4.4 Project benefit analysis

At the conclusion of the detailed design process summarised in section 4.2, a project benefit and risk analysis was carried out in order. This was intended to aid evaluation of the project and assess the primary risks and define what elements of the proposed structure necessitate further investigation prior to investing further resources in detailed development of the proposed project. The following is a summary of the primary benefits the project is expected to deliver whilst the risks are presented in section 4.5.

- **Absolute lightweighting potential of approximately 260 kg.** This is equivalent to an additional capacity of approximately four passengers.
- An **enabler of further step-change lightweighting** of the bus. As was detailed in submission #2, a feasibility study carried out on the lightweighting of the chassis concluded that the weight reduction (in excess of 1000 kg) of the chassis would not have been possible to be implemented as the bus would fail to pass the 28° tilt-test requirement. As illustrated in Figure 4.10, at a 28° inclination a 100 kg reduction in weight of the upper-deck structure would enable a 700 kg reduction in the weight of the chassis structure to be implemented. Such a radical reduction in weight would enable other secondary weight reduction achieved through downsizing of systems such as the drivetrain.

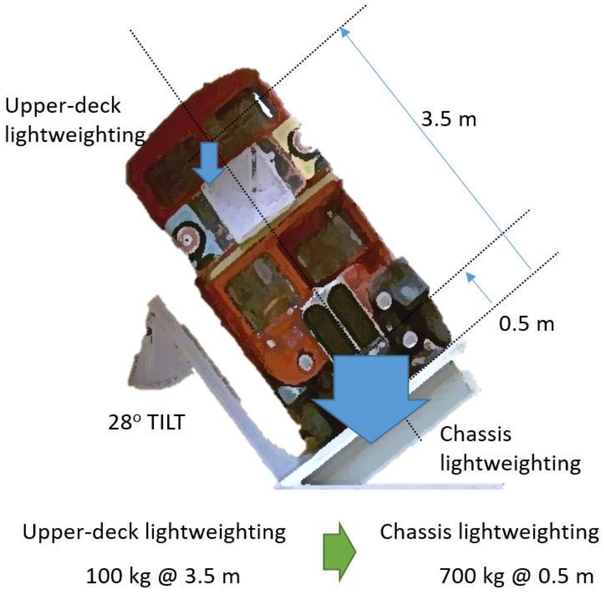


Figure 4.10: Lightweighting of the upper-deck structure is an essential enabler for further bus lightweighting.

- **Lightweighting of the structure with the 'highest' centre of gravity location.** The upper-deck structure is the highest main sub-structure of the bus hence this lightweighting would result in a significant lowering of the centre of gravity. The lowering of the centre of gravity could help enhance the ride stability and hence passenger comfort. The reduction of the vertical polar moment of inertia would translate to a reduction of pitch and roll of the bus during operation.
- **Electrification of the drivetrain.** As the industry moves towards the electrification of the drivetrain, lightweighting of the structure would result in either extended autonomous range and/or smaller and hence cheaper battery pack.
- **Possibility of new market penetration.** The striking panoramic upper-deck structure could offer the opportunity to attract new clients seeking to utilise the bus on tourist routes. The significant increase in glazing should enhance the experience of passengers seated in the upper-deck cabin.
- **Relatively low risk and low investment project.** As will be detailed in submissions #5 and #7, the two novel primary structural elements which are being introduced to ADL in this project, do not require extensive investment in tooling. Additionally, the project could be introduced in phases without having to alter the main assembly lines.
- **Lifetime fuel savings of £2,600 per bus.** As has been estimated in submission #2, as a direct consequence of the estimated lightweighting, a lifetime running cost reduction

of £10/kg lightweighting should be achieved. Another cost benefit is achieved through the elimination of costly glass window breakages.

- **Increased passenger safety.** As detailed in section 3.2.3, the emergence of passengers from the bus through broken glass windows in case of accidents has become one of the biggest causes of fatality in case of accident. It is expected that the superior impact-resistance performance of polycarbonate glazing would reduce these fatalities.

## 4.5 Review of project critical risks

The main driver behind the project was lightweighting, hence the confidence in achieving the estimated lightweighting was assessed. It has been detailed in section 4.3 that the weight estimates of the primary structural components are all based on conservative estimates and hence there is a high degree of confidence that the estimated structural lightweighting would be achieved once the structure is realised.

Additionally, the structure is not part of the bus primary structure and hence, not a safety-critical component of the bus. This significantly reduces the project risk, and provides an ideal structure for the company to introduce novel structural members and materials. The consequences of an unforeseen failure mode during the lifetime would be much less severe than if the structure was a primary structural element which would potentially necessitate the bus to be removed from service until the issue is resolved.

### 4.5.1 Project cost

In such a cost-sensitive market, one of the critical risks to the project is cost. The low-volume nature of the industry would typically rule out investment-heavy manufacturing technologies because even if the net-component cost would be within acceptable limits it would not be possible to amortise the research, development and testing investment. As such, cost was taken into consideration from the start of the design conception.

The cost of the roof sandwich panel including the integrated cantrail beams will be reduced as their size is reduced by about a third. On the other hand, the cost of the curved vertical beams and the polycarbonate glazing panels will undoubtedly be higher than the current configuration of aluminium extrusion beams and glass glazing. This increase in cost could be partly offset by the cost reduction of the roof panel but in order to assess in detail the cost impact of the project, further research and development are required.

### 4.5.2 Lifetime performance of polycarbonate glazing

One of the critical components of the proposed structure is the polycarbonate glazing panels (approximately 50% of the weight saving). As introduced in section 3.3.3, polycarbonate glazing suffers from very low scratch-resistance and degrades when exposed to UV radiation. Therefore, it is only suitable to be utilised as a glazing material when coated. The utilisation of polycarbonate glazing within the automotive industry is limited and hence there is very limited information of the lifetime performance of these materials. There is even less information about the performance of such glazing materials within the bus industry, which could expose these glazing panels to particularly harsh environments. An unsatisfactory performance of the coated polycarbonate glazing panels being proposed is hence identified as one of the key risks of this project. It could be argued that even if the lightweight polycarbonate glazing would be replaced by 5 mm laminated glass panels, the proposed structure would still be able to achieve about 20% lightweighting whilst retaining the other benefits that the proposed structure could offer.

### 4.5.3 Technology maturity level of primary components

A key uncertainty for the cost of the project is that two of the key structural elements (the curved beams and the polycarbonate glazing) are not at a mature technology readiness (TRL) level in the bus sector. Both technologies are more mature in other industries and the challenge is to transfer these technologies over to the bus industry at an industry feasible cost point.

## 4.6 Design review conclusions

The implementation of such a project would require investment and commitment by ADL. ADL have confirmed that they consider the potential of the project to be significant and they would be looking at investing in further development of the concept and hence the next stage was to address the most significant risks of the project in order to increase the confidence in the proposed structure.

Thus, the two main areas of research identified and agreed between ADL and WMG which were pursued during the remainder of this EngD research project were the following:

- **Fibre reinforced composite braided beam structures.** ADL expressed significant interest in investigating the feasibility of utilisation of braided FR composite beam structures and hence, a work package to assess the design, manufacturability and cost of these beam structures was carried out with a summary of the outcomes presented in chapter 5.
- **Coated polycarbonate glazing.** An investigation on the utilisation of this technology within the bus industry was made in collaboration with the leading PC manufacturer – Sabic. The results of this investigation are presented in chapter 6.

# 5

# BRAIDED FR COMPOSITE BEAM STRUCTURES WITHIN THE BUS INDUSTRY

An integral component of the lightweight upper-deck structure detailed in chapter 4 is the set of curved structural beams illustrated in Figure 5.1. This chapter summarises a series of work packages carried out to assess feasibility of braided fibre reinforced (FR) polymer composite beams in bus structures. The objectives of the research were:

- Identification of a cost-feasible system for the manufacture of braided FR beams taking into consideration bus-industry volumes and constraints.
- Development of a methodology to enable ADL to effectively design and model beam structures manufactured by the identified method.
- Manufacture of demonstrator components for verification.

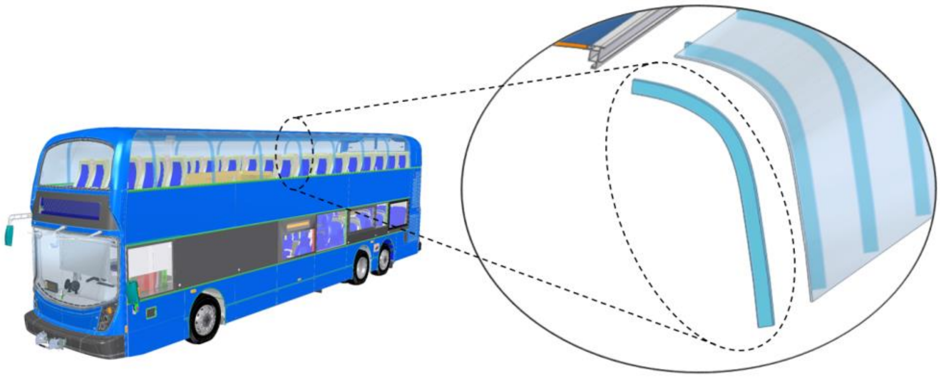


Figure 5.1: An integral component of the proposed lightweight upper-deck structure is the set of curved structural beams.

## 5.1 Lightweight composite curved beam structures

FR polymer composite structures allow the designer an extensive choice of materials and manufacturing systems. A review was carried out to identify a combination of material systems and manufacturing method mostly suitable to manufacture hollow composite beam structure for integration on ADL bus structures. These structures are novel to ADL and hence a low capital-investment solution which allows a gradual programme of testing and implementation was a key driver to this review.

### 5.1.1 Fibre-reinforced polymer-matrix composite structures

Continuous fibre-reinforced polymer matrix composite structures are increasingly penetrating engineering products in various industries and in particular in transportation industries. They offer various advantages including high specific strength and stiffness offering lightweighting opportunities, corrosion and fatigue resistance thus, reducing product maintenance costs. Additionally, they typically offer excellent design and manufacturing flexibility [126].

FR composite structures consist of two primary components; fibres and matrix. The mechanical properties of the composite material are significantly dependent on the properties of the fibres, as well as the interface between the fibre and matrix material (surface interaction), fibre volume fraction and orientation of the fibres within the composite. Textile composites (e.g. woven, knitted and braided fabrics [127]) are a subset of continuous fibre reinforced composites composed of textile structures embedded in a polymer resin matrix. They are being increasingly adopted as they offer several advantages over conventional laminate structures including high volume and automated production rates and improved structural stability and damage tolerance as a result of yarn interlacing [128]. Due to these clear advantages the utilisation of textile composites is increasing in various industries including aerospace, marine, automotive, and sports [128–130].

### 5.1.2 Braided beam structures

The conventional manufacturing technique of producing straight FR composite beams is the pultrusion process. This is similar to metal extrusion but in this case the polymer matrix and the reinforcing fibres are pulled through a heated forming die taking the net shape [131]. Pultrusion is a cost-effective composite beam manufacturing process, however, it is mainly limited to the production of straight beams. A variation of the pultrusion process capable of producing curved beams has been recently developed but the process is constrained to beams having constant radius curvature [132].

Apart from pultrusion, braiding is an extremely cost effective process for the production of tubular fibre preforms for polymer-matrix composite hollow beam structures. This is due to several factors including a relatively high layup speed, a readily automated process and minimal material wastage as typically a net fibre preform is produced. Braiding is extremely versatile in terms of the types of fabrics and shapes that it can produce [133]. The basic elements of the braiding process and how it is typically automated using a maypole braider are illustrated in Figure 5.2.

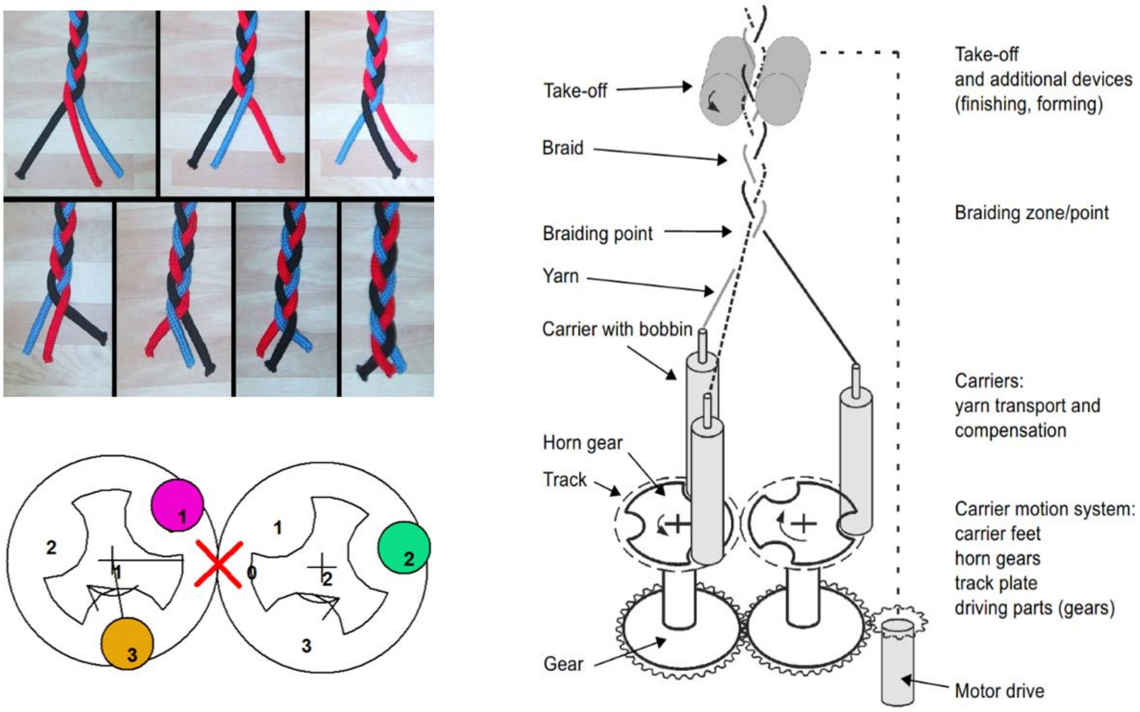


Figure 5.2: Description of the braiding process. Two sets of braiding bobbins (numbered 1, 2 and 3) are rotated in opposite directions along the braiding track. The braid is created at the braiding point typically over a mandrel which is pulled by a take-off mechanism, adopted from [134].

Yarns of fibres are wound onto the bobbins which are loaded onto the braiding track. In biaxial braiding, two sets of bobbins rotate along the braiding track in undulating circular paths in opposite directions hence intertwining the yarns as they are guided by the braiding ring onto the braiding mandrel. The fibres in the braided preform are mechanically interlocked and have natural conformability which allows the braid to fit over complex shapes. By controlling the speed of the mandrel movement along the take-up direction, the braid angle is controlled, which in turn has a significant effect on the mechanical properties of the composite component. For complex curved components, the mandrel is mounted onto a robotic arm which can rotate and move the mandrel as necessary to ensure accurate control of the braid angle. Additionally, the braided preform can be passed back through the braider in order to add as many over-braided layers as necessary to achieve the required structure wall thickness. This high-output process can be readily automated.

Once the braided preform is manufactured, a fibre and matrix consolidation process is necessary to obtain the final structure. The typical process of impregnation and consolidation of braided preform structures is resin transfer moulding (RTM) process. The RTM process occurs in a rigid closed mould. The braided preform is placed on one side of the tool, and then the other side of the tool is closed. A liquid resin is then injected into the tool through appropriate gates displacing the air entrapped within the braided preform. A vacuum can be applied to assist with the extraction of this air hence aiding the impregnation process. Once the impregnation process is complete and resin cure is complete, the tool is opened and the finished structural component released. The core of the braided preform resists the pressure loadings imposed by the injected resin. When the braided preform does not have a core, a silicone bladder is inserted within the braided preform and inflated so that the fibre preform is held in shape against the tool face whilst the matrix resin injected. The process of bladder-assisted RTM of a braided preform is illustrated in Figure 5.3.

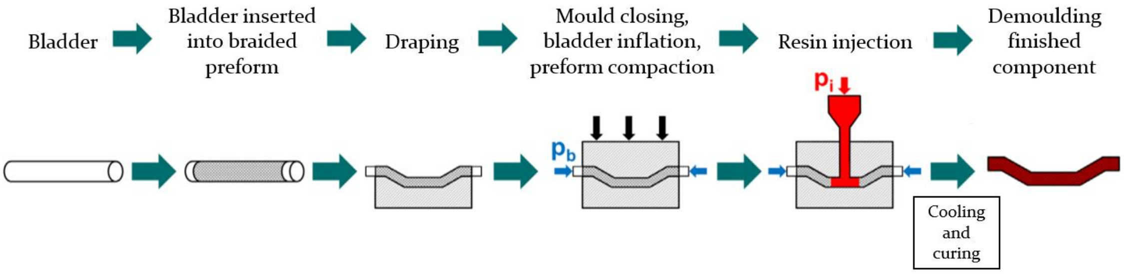


Figure 5.3: Tubular fabrics in bladder-assisted resin transfer moulding, adopted from [135].

A well designed RTM process is capable of producing complex parts having high mechanical performance and very good dimensional tolerances. This technique offers cost-effective parts in medium to high volume scenarios [136]. To ensure the required performance from the final component, the RTM process needs to guarantee the complete and uniform impregnation of the preform with resin. The incorrect control of compaction and impregnation during the composite consolidation stage would result in a number of defects which are typically classed as either voids and/or dry spots which in turn results in loss and gradual degradation of mechanical properties. Tool development and design as well as precise control of the RTM process are essential to ensure uniform quality of the composite part.

The combination of the braiding process and a thermoplastic (TP) matrix offer the tantalising possibility of a very efficient manufacturing process opportunity possibly avoiding several of the technical issues and costs associated with the RTM process. The capacity of thermoplastics to be re-melted upon the application of heat implies that if the thermoplastic matrix is added to the reinforcing fibres during the braiding process, the braided preform would necessitate heating above the melting point in order for the fibre-matrix consolidation to occur. Mixing of the reinforcing fibres and matrix polymer can be achieved through the utilisation of hybrid yarns during the braiding process. As illustrated in Figure 5.4, upon the application of heat to the polymer/fibre yarns, the polymer melts and starts impregnating the fibres. The application of pressure aids the process and helps to reduce the voids giving a consolidated composite structure.

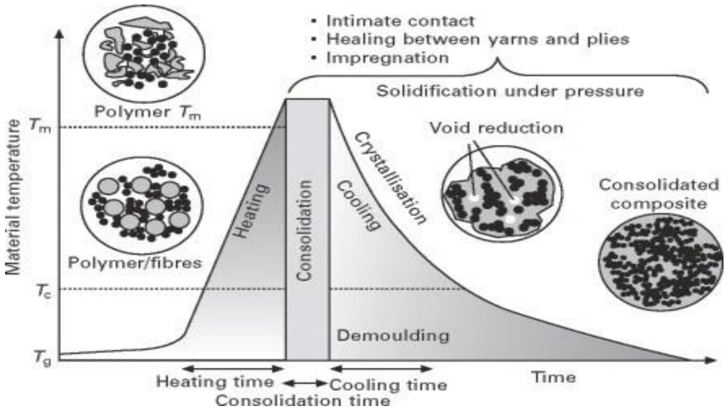


Figure 5.4: The consolidation of braided thermoplastic hybrid yarns upon the application of heat, reproduced from [137].

### 5.1.3 Bladder-assisted consolidation of TP braided FR composite beams

The state-of-the-art review showed that pultruded fibre reinforced (FR) polymer composite beams are finding commercial applications within the bus industry [138]. However, this technology is not suitable for variable-radius curved beams. Similar to pultrusion, braiding offers an automated, efficient method for producing the fibre preforms. Out of various possibilities of consolidating braiding preforms, the utilisation of hybrid commingled yarns which are subsequently consolidated by heating in a tool was considered to be the most viable option. The rationale behind the proposed material and manufacturing system, illustrated in Figure 5.5, was based on the following considerations:

- Demonstrator and low-volume production require low capital investment. The design and manufacture of a simple metal forming tool (typically less than £5,000) are the only project-specific investment needed.
- The utilisation of hybrid commingled yarns eliminate the need for complex RTM tooling whilst still achieving composite structures of the required quality.
- The use of a bladder-based system as opposed to braiding over a permanent solid core avoids the cost of development and manufacture of the core as well as enables better control of the consolidation process.
- Feasibility of increasing rate of production by investment in high-volume tooling utilising same material system previously verified during the concept development and verification stage.

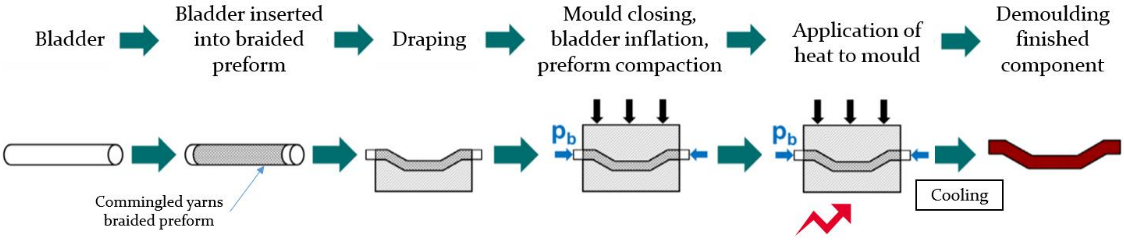


Figure 5.5: Bladder-assisted consolidation of thermoplastic braided FR composite beam structures, adopted from [135].

## 5.2 Manufacturing of demonstrator braided FR beam structures

A work package was organised to assess the feasibility of the proposed solution for the production of the upper-deck structure curved beams. The manufacturing process illustrated in Figure 5.5 was followed to manufacture demonstrator beam sections. Besides verification of the proposed manufacturing process, this allowed an analysis of the manufacturing costs. Finally, mechanical testing of the demonstrator beams enabled the verification of a design methodology as detailed in section 5.3.

A UK-based company with whom this collaborative research-project was carried out was identified by the author. Composite Braiding Ltd. is a company specialising in the manufacture of thermoplastic braided composite structures [139]. The process consisted of two main stages; manufacture of the braided preforms and the bladder-assisted consolidation of the braided preform.

## 5.2.1 Braiding of the preform

The first stage of the manufacturing process consisted of the braiding of the preform structure. E-glass/polyamide (PA6) commingled fibres manufactured by Coats Group plc. [140] were used. These hybrid yarns were supplied ready wound on bobbins which can be directly mounted onto the maypole braiding machine illustrated in Figure 5.6.

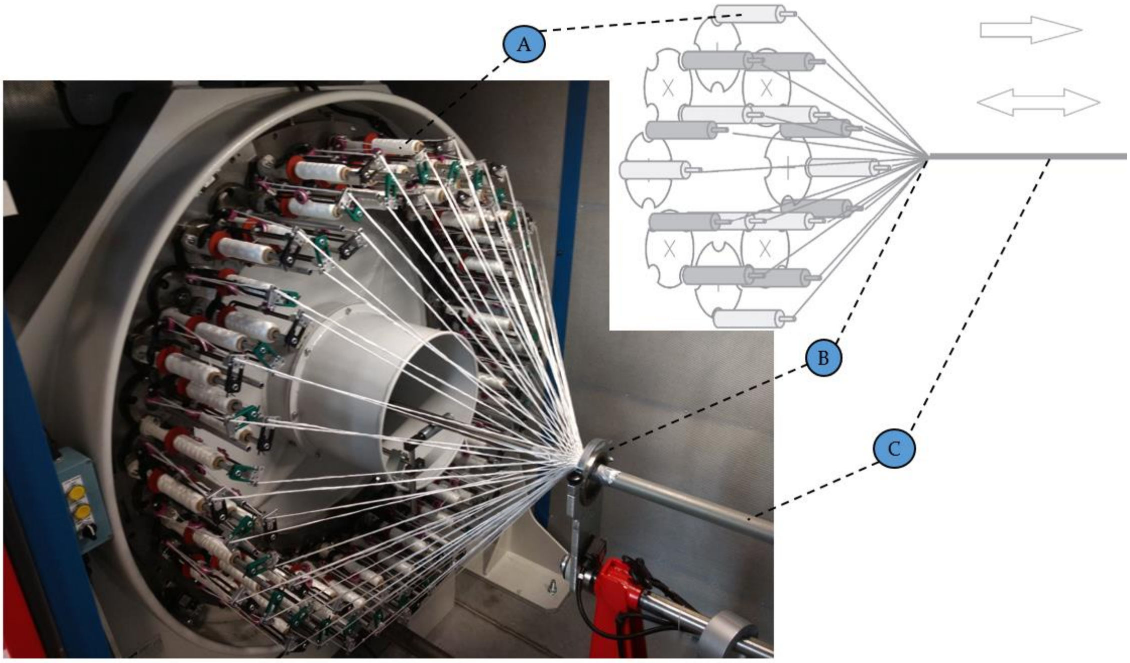


Figure 5.6: The 48 bobbin braiding machine used to manufacture the braided preforms at Composite Braiding Ltd. Commingled yarns are released from the bobbins (A) and intertwined to form the braided preform (B) over a steel mandrel (C), adopted from [134].

The preform was braided over a steel tube mandrel. As the mandrel was pulled through the braiding ring, the braided preform was laid on the mandrel. The control and synchronisation of the mandrel movement speed and the braiding bobbin rotation together with the diameter of the mandrel define the braiding angle of the braid. Once the required length of preform was braided, the direction of movement of the mandrel was reversed so that another layer could be over-braided. This was repeated until the number of layers as required by the final component were braided. The preform was then released from the mandrel, which was reutilised to braid the other preforms. The braiding process is extremely efficient, a 48 bobbin braider such as the one shown in Figure 5.6 is capable of braiding 700 metres/day of preforms with a size and shape similar to what is being evaluated. Detailed productivity calculations could be carried out utilising modelling software supplied with some braiding machines or analytically calculated [141].

### 5.2.2 Fibre-matrix consolidation stage

An overview of the different steps involved in the consolidation of the braided preforms is presented in Figure 5.7.

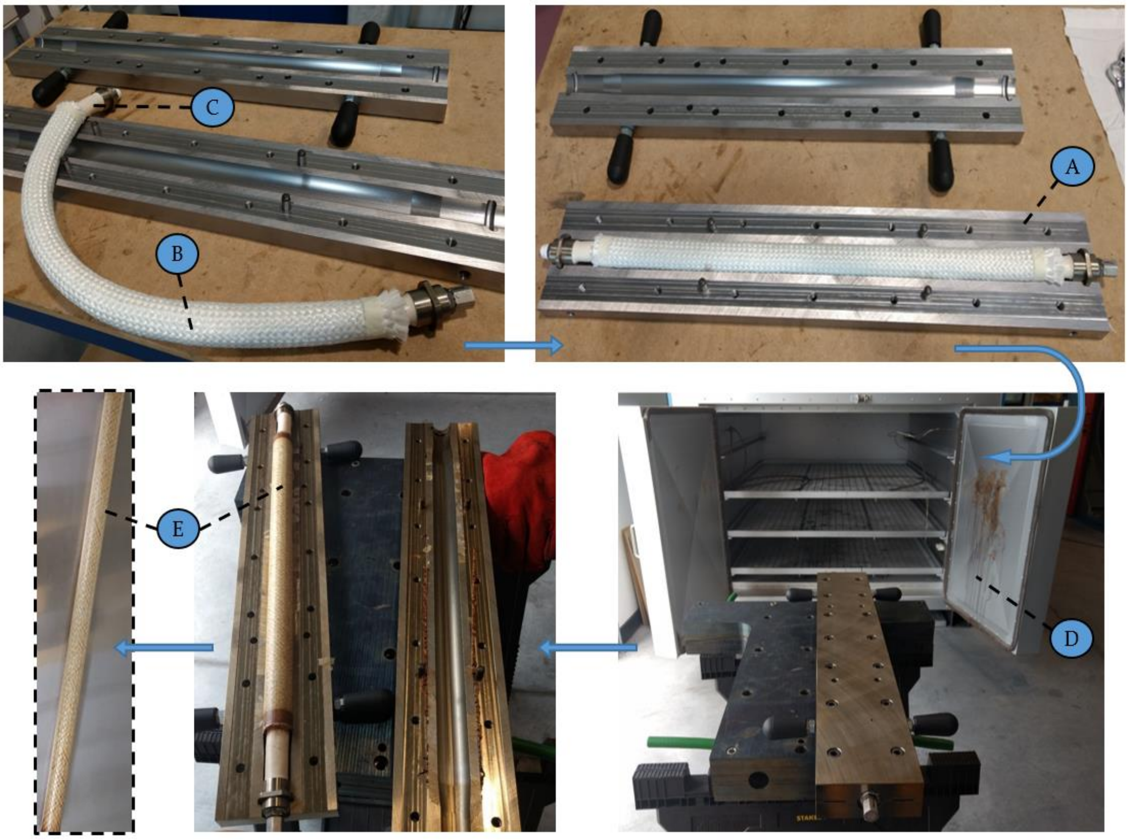


Figure 5.7: An overview of the proposed bladder-assisted consolidation of a braided FR thermoplastic structure. The braided composite preform (B) is supported by an inflatable bladder (C), placed within a simple metal tool (A) and heated within a conventional oven (D) in order to achieve the final consolidated component (E)

Once the braided preform was ready and released from the braiding mandrel, an inflatable silicone bladder was inserted into the preform. The metal forming tool illustrated in Figure 5.7 presents the appropriate thermal conductivity and is able to resist the internal pressure loadings imposed by the preform during the consolidation process. The preform was then placed within the forming tool. The flexible preform conforms to the tool shape and the same preform could be utilised to manufacture beams having different curvature profiles. The tool was then closed and the two sides of the tool bolted together. The silicone bladder was attached to a compressed air supply and the tool inserted into an oven. The oven and hence the tool were heated up to 240°C (approximately 20°C above the melting temperature of PA6) at which point the internal bladder pressure was increased to 20 bar to aid the fibre-matrix consolidation process. The tool was held at this temperature for ten minutes following which the oven is cooled until the temperature of interior face of the tool is below the stress-free temperature (crystallisation temperature in case of a semi-crystalline polymer) of the matrix material at which point the tool was opened and the finished component released as shown in Figure 5.7. Total cycle time for this particular set-up was approximately 240 minutes. Once the component was released from tool, the inflatable bladder was removed and reused.

### 5.2.3 Option for higher volume production

The proposed method of using a bladder-assisted consolidation in a passive-heated tool is well suited for demonstrator or low volume production runs due its inherent low-investment cost (design and manufacture of a simple metal tool). Production volumes are limited by the consolidation process cycle time which in this case was 240 minutes. A possible mitigation technique would be to simultaneously use multiple consolidation tools, otherwise a tool that would enable rapid heating and cooling of the tool forming faces would be needed.

A technology developed by a UK based tool manufacturer, Surface Generation Ltd (SG), was identified as a possible solution. SG have developed a rapid heating tool system called "Production to Functional Specification" (PTFS) [142]. The system allows efficient, localised and rapid heating of the tool surface typically achieving a heating rate of approximately 30°Cmin$^{-1}$. This would enable a takt time of approximately 20 minutes (7 minutes heat up, 6 minutes composite consolidation dwell time, 7 minute cool down). SG have indicated that this can be optimised and takt times of less than ten minutes is achievable. SG have not yet built tools for the manufacture of a bladder-assisted consolidation process, however, following initial feasibility discussions, no technical complexities that could prevent this technology from being translated to this application were foreseen. At time of writing, a research project to further investigate the proposed system is being developed at the University of Warwick.

## 5.3 FE modelling of fibre-reinforced braided structures

Finite element (FE) modelling has become an integral part of the engineering design process. It allows the design and optimisation of a structure to occur in a virtual environment drastically reducing the amount of physical testing and verification. The material system and manufacturing process being proposed allows the designer a high degree of customisation. The properties of the final beam structure depend on the fibre and matrix properties, but are also significantly dependent on the braiding process parameters with the two critical parameters being the braid angle and the number of over-braided layers. Given the number of variables, a methodology for effective modelling of these structures is essential. The definition of a suitable methodology was intended to allow the design process of the required curved beams but also serve as a design tool for ADL to evaluate the feasibility of integrating braided beam structures into other systems on the bus. The development of the proposed design methodology consisted of the following main work packages:

- Manufacture of a number of test-beam using the method detailed in section 5.2.
- Three-point bend flexural loading of manufactured beams.
- Set-up of an FE model simulating the three-point bend testing.
- Correlation of the results from the physical testing with the FE model simulation.

### 5.3.1 Test-beam manufacture details

The first work package consisted of manufacturing a number of demonstrator beam sections as detailed in section 5.2. Twelve straight tube sections having a length of 500 mm were manufactured. The main properties of raw materials and parameters of the manufacturing process are presented in Table 5.1. These parameters were established with the industrial partners based on previous process development experience and input from the commingled fibres' supplier.

Table 5.1: Braiding and consolidation process parameters utilised during the manufacture of test beams

| Process | Parameter | Detail |
|---|---|---|
| Commingled yarns properties | Material | E-glass / PA6 |
| | Tow thickness | 0.22 mm |
| | Tow width | 3.6 mm |
| | % volume fibre fraction | 55 % |
| Braiding process parameters | Braiding angle | $25^0$ |
| | Braid type | Five over-braided regular (2 × 2 twill) biaxial layers |
| | No. of braiding carriers | 48 |
| Consolidation process parameters | Max. temperature | 240°C |
| | Consolidation time hold | 10 minutes |
| | Total cycle time | 240 minutes |
| | Pressure at consolidation | 20 bar |
| Final component | Outside diameter (O/D): | 35 ± 0.25 mm |
| | Wall Thickness: | 2.5 ± 0.25 mm |
| | Weight | 440 grm$^{-1}$ |

## 5.3.2 Mechanical properties testing: three-point flexural testing

The primary type of loading that the beams experience in service is flexural loading induced by road loads into the bus structure. This loading can be modelled using a three-point bend test. Classical beam theory was used to analyse the results of the three point bend tests [143, 144]. For a simply supported beam, loaded with a load $'P'$ at mid-span “$l/2'$, the maximum deflection at mid-span ‘$\delta_{max}$’ as illustrated in Figure 5.8 is calculated using Equation 5.1.

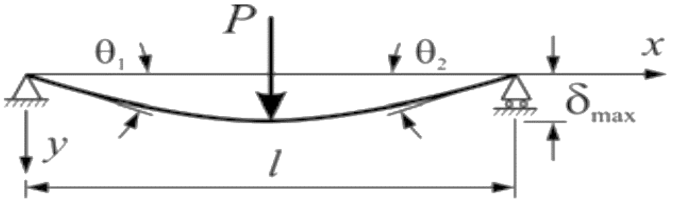


Figure 5.8: Maximum deflection ($\delta_{max}$) of a simply supported beam loaded at mid-span of the free-spanning length (l) with a flexural load (P).

$$\delta_{max} = \frac{Pl^3}{48\mathrm{E_b}I}$$

Equation 5.1

Rearranging the formula for maximum deflection of the simply supported beam Equation 5.1) allows the determination of the bending modulus of the beam structure as indicated by Equation 5.2.

$$E_b = \frac{l^3}{48.I} . \left[\frac{\Delta P}{\Delta \delta}\right] = \frac{l^3}{48.\left[\frac{\pi}{4}(r_o^4 - r_i^4)\right]} . \left[\frac{\Delta P}{\Delta \delta}\right] = \frac{l^3}{12\pi(r_o^4 - r_i^4)} . \left[\frac{\Delta P}{\Delta \delta}\right] \tag{Equation 5.2}$$

| | |
|---|---|
| $\delta_{max}$ | Maximum deflection of beam |
| $l$ | Free-span length of beam |
| $r_o,\ r_i$ | Outer and inner radii of the tube being tested |
| $\left[\frac{\Delta P}{\Delta \delta}\right]$ | Gradient of the load (P) vs. deflection (δ) curve that is obtained during the three-point-bend flexural test |
| $E_b$ | Flexural bending modulus |
| $I$ | Second moment of area of the beam cross section |

### 5.3.2.1 Testing methodology

The three-point flexural loading set-up was implemented utilising an Instron 5800R tensile/compression test system with loading capacity of ±100 kN. The mechanical arrangement consisted of a three-point loading rig as illustrated in Figure 5.9. Steel tubes were initially tested to validate the arrangement, following which the braided FR tubes were tested.

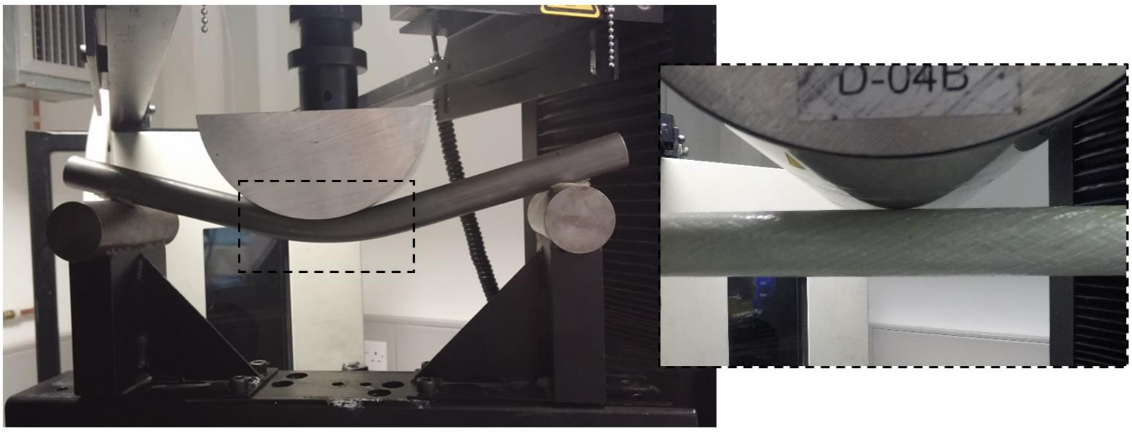


Figure 5.9: Left: The three-point bend support and load-anvil set-up. Left: Flexural loading of a steel tube at an extension of approximately 35 mm. Right: Braided FR tube at commencement of loading.

Testing of the FR tubes was carried out by imposing on the beams a constant deflection rate of 17 mm/min, and the reactive load imposed by the beam onto the moving impactor was recorded by a 100 kN load cell. A record of the load (P) v.s. deflection (δ) was obtained from the test system to enable further analysis of the test results.

#### 5.3.2.2 Test results

The results of three-point bend testing carried are presented in Table 5.2. The presented data is the average of twelve tubes manufactured as per the details presented in Table 5.1.

Table 5.2: Results and analysis of three-point flexural loading of 400 mm span tubes (12 samples tested, 35 mm OD, 2.5 mm wall thickness, 440 gm$^{-1}$).

| diameter | Wall thick-ness | $I_{xx}$ | Mass | $\rho$ | $P_{max}$ | $\delta_{max}$ | $M_b$ | $\sigma_{yield}$ | $\left[\frac{\Delta P}{\Delta \delta}\right]$ | $E_b$ | $\left[\frac{\Delta P}{\Delta \delta}\right] m^{-1}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| mm | mm | mm$^{-4}$ | kgm$^{-1}$ | kg / m$^3$ | N | mm | Nm | MPa | Nmm$^{-1}$ | GPa | (N/mm) / kg |
| 35 | 2.5 | $3.4\times 10^{-8}$ | 0.44 | 1724 | 1405 | 6 | 140 | 24.8 | 241.8 | 9.5 | 550 |

### 5.3.3 FE model

Various researchers have developed models for modelling textile composites [129, 130, 145]. A comprehensive review of modelling techniques utilised for the prediction of fabric textile composite concluded that the utilisation of macro-scale FE modelling combined with theoretical analysis of the unit-cell composite properties yields reasonable results whilst being the most cost effective and efficient modelling technique [130]. This approach was successfully utilised by Melenka et al. to model tubular braided composites and hence the modelling methodology utilised by the same was followed in this project [146].

#### 5.3.3.1 Analytical derivation of mechanical properties of braided material

The initial step of the proposed FE-based design methodology is the analytical derivation of the properties of the braided composite material. This method combines the properties of the raw materials (i.e. the fibre and the matrix mechanical properties) together with the primary braiding process parameters in order to calculate the properties of the final composite materials as illustrated in Figure 5.10.

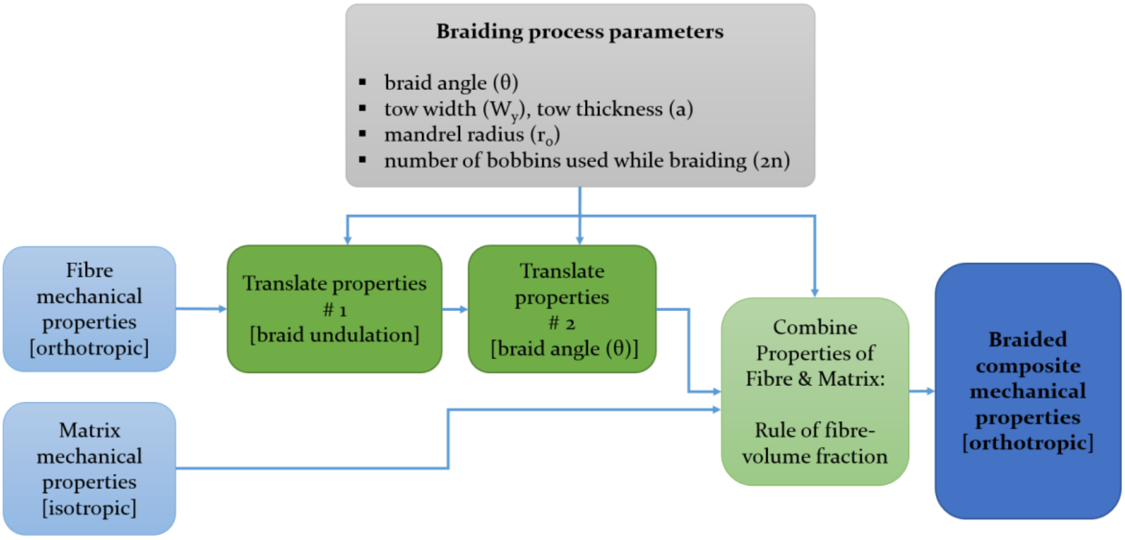


Figure 5.10: The mechanical orthotropic properties of the braided composite material are analytically derived from the mechanical properties of the fibre and matrix materials taking into consideration the braiding process parameters.

The analytical model developed in 2017 by Melenka et al. was applied in order to derive the orthotropic material properties that could be inputted into a macro-Fe-model of the braided tube structure [146]. The orthotropic properties of the fibres (in their local x-y-z coordinates) were inserted in the compliance matrix, which was subsequently inverted in order to obtain the stiffness matrix. The stiffness matrix was then transformed twice in order to translate the properties of the fibres from the local fibre-axis to the braided structure's global axis. As illustrated in Figure 5.11, the first translation (#1) takes into consideration the unit undulation length and height which are directly related to the braiding process parameters listed above. The mechanical properties along one braid unit cell are integrated and averaged in order to account for the varying direction of the fibre. The averaged mechanical properties along the direction of the yarn are then translated from the yarn axis towards the structures' global axis (#2).

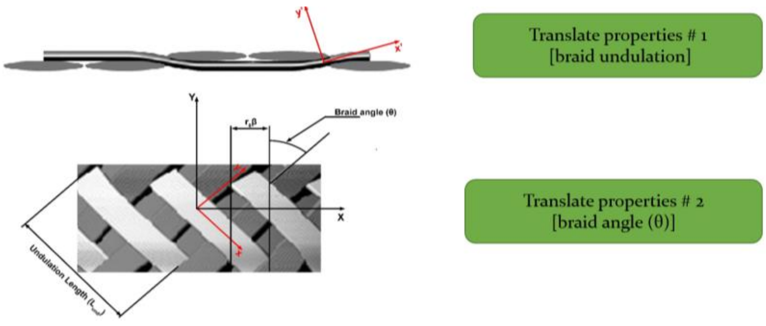


Figure 5.11: Translation of mechanical properties. Firstly, the effects of the braid undulations are integrated and averaged over a braid unit cell (translation #1) and secondly these properties are translated to the principal braiding axis from the fibre axis considering the braid angle (translation #1), adopted from [146].

Once the stiffness matrix of the braided tow transformed into the tube global coordinate system $[C^{+}_{xyz}]$ is obtained, the combined stiffness of the braided material could be calculated using the rule of mixture. In the case of a biaxial braid, there are three components within the composite; the clockwise fibre yarn with stiffness matrix $[C^{+}_{xyz}]$, the anti-clockwise fibre yarn with stiffness matrix $[C^{-}_{xyz}]$ and the matrix with stiffness matrix $[C^{m}_{xyz}]$. Hence, the global stiffness $[C^{G}]$ is worked out utilising Equation 5.3 where $V_{f\theta}$ and $V_m$ are the volume fraction of the fibre and matrix respectively.

$$[C^{G}] = V_{f\theta+}[C^{+}_{XYZ}] + V_{f\theta-}[C^{-}_{XYZ}] + V_{fm}[C^{m}_{XYZ}] \qquad \text{Equation 5.3}$$

This process was followed to derive the mechanical properties of the consolidated composite material of the manufactured beams. The mechanical properties of the constituent fibre and matrix materials and the braiding process parameters that were utilised as well as the analytically derived mechanical properties of the composite materials are presented in Table 5.3. The derived mechanical properties of the composite materials were then utilised in a simple linear-elastic FE model where the braided material was modelled as a constant homogenous orthotropic material.

Table 5.3: Mechanical properties of the commingled yarns constituent materials (supplied by commingled yarns manufacturer) and analytically derived properties of the consolidated composite structure.

**Material elastic properties of fibre (E-Glass) and matrix (PA6)**

| | **$E_1$** GPa | **$E_2$** GPa | **$E_3$** GPa | **$G_{12}$** GPa | **$G_{13}$** GPa | **$G_{23}$** GPa | **$\nu_{12}$** | **$\nu_{13}$** | **$\nu_{23}$** |
|---|---|---|---|---|---|---|---|---|---|
| **Fibre** | 72 | 72 | 72 | 30 | 30 | 27 | 0.2 | 0.2 | 0.2 |
| **Matrix** | 0.7 | 0.7 | 0.7 | 0.28 | 0.28 | 0.28 | 0.3 | 0.3 | 0.34 |
| **Composite** | 14.169 | 14.114 | 14.116 | 5.864 | 5.400 | 5.764 | .2045 | .2045 | .2057 |

| | |
|---|---|
| **$E_1$** | Longitudinal elastic modulus |
| **$E_2$, $E_3$** | Out-of-plane moduli |
| **$G_{12}$, $G_{13}$** | In plane shear modulus |
| **$G_{23}$** | Out-of-plane shear modulus |
| **$\nu_{12}$, $\nu_{13}$** | In-plane shear |
| **$\nu_{23}$** | Out-of-plane Poisson’s ratio |

### 5.3.3.2 FE model set-up

The commercially available FE solver LS-Dyna [147] was utilised to set up the model of the three point bend tests that were carried out as illustrated in Figure 5.12. The material cards available in typical FE software packages are mostly based on phenomenological material models (i.e. the material is treated as a homogenous continuum – averaging the performance of the fibres and the matrix). Given that the scope of this model is limited to elastic loading response, the *MAT_ORTHOTROPIC_ELASTIC* material card (*MAT_002* in LS_DYNA) was utilised to which the derived properties presented in Table 5.3 were submitted. Belytschko-Tsay elements sized at 2 mm × 2 mm with five through thickness integration points were utilised to model the beam. LS_Dyna indicate that Belytschko-Tsay elements are the most economical shell elements and should be used unless particular features are required which was not deemed the case in this situation [147]. The number of integration points (5) was chosen to match the number of over braided composite layers so that the deformation of the different layers could be analysed if necessary. The size of the element was determined following a mesh-size sensitivity analysis exercise. The contact between the beam and the supports and impactor were defined utilising the '*Automatic_Surface_to_Surface*' contact card.

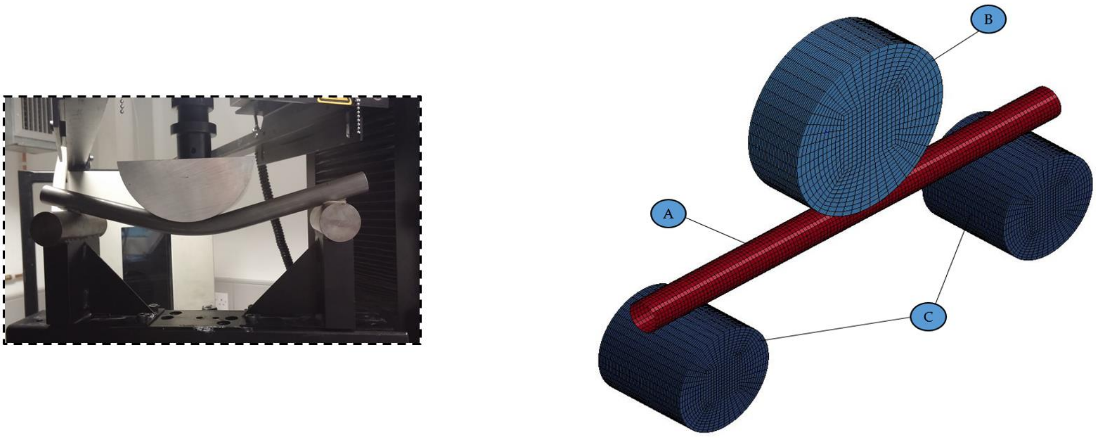


Figure 5.12: FE model of the three-point bend loading of test beams. Vertical movement imposed on the impactor (B) results in flexural loading of test beam (A) supported on rigid supports (C).

## 5.3.4 Correlation of FE model to measured data

The FE model was solved to output a simulated loading vs. extension curve which was compared to the results from the physical testing as illustrated in Figure 5.13. This correlation exercise was intended to verify the accuracy of the proposed FE methodology in modelling braided composite structures loaded under linear elastic conditions. Linear data fitting over the elastic region between flexural extensions of 1.5 mm and 5 mm were considered for the comparison. The initial 1.5 mm of flexural extension was not included as data in this initial loading of the structure might include inaccuracies such as test-frame compliance as well as flexing of the beam cross-section.

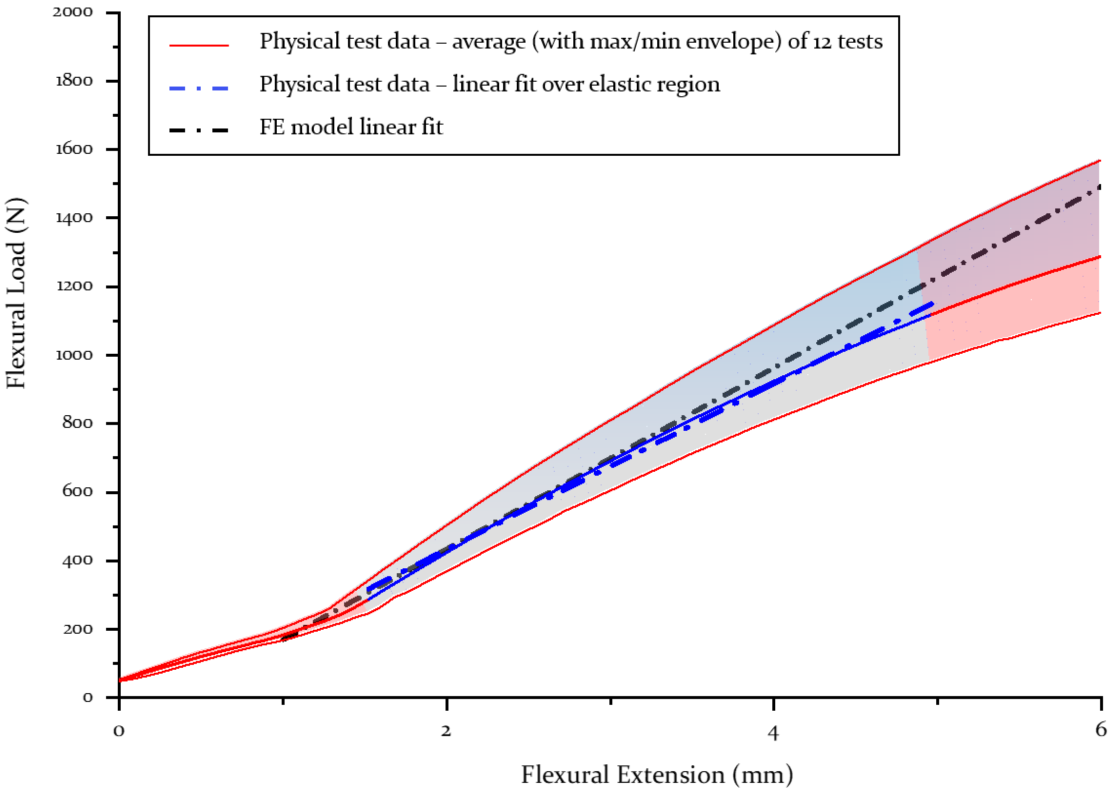


Figure 5.13: Correlation of three-point bend physical testing (average of 12 tests) [241.8 Nmm$^{-1}$] to the simulated FE model [264.4 Nmm$^{-1}$]. FE model over-predicting stiffness by 9%.

The FE simulation over-estimates the flexural stiffness of the tube structure by approximately 9%. This over-estimation of flexural stiffness by the FE model was somewhat expected. In practice, composite structures have several sources of uncertainty in their performance due to composite material property variations and manufacturing process variations which include variations in geometry, thickness, control of fibre alignment etc. [148]. This uncertainty is typically accounted for through the utilisation of design safety factors which are sometimes mandated by certification agencies such as the case in the aerospace industry [149]. Although more repeated testing and variations would be necessary in order to increase the statistical confidence in the required safety factor that would need to be applied during the design stage to account for the described composite variability factors, a safety factor of at least 1.2 should be applied given the 9% over-estimation by the FE model in this correlation exercise.

A plot of the von-Mises stresses at the yield point during the three-point bend test FE simulation is illustrated by Figure 5.14. It must be emphasized that the material card data and hence the FE model are only valid in linear elastic loading conditions.  The results of the physical testing indicated yield loading occurs at 6 mm flexural deflection, and hence the effective stress at yield could be determined from the FE Model.

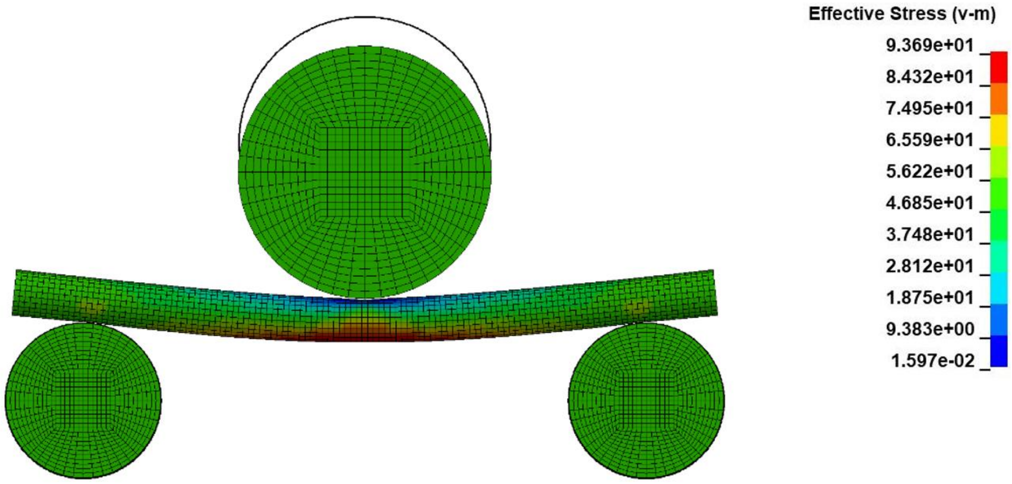


Figure 5.14: Results of FE model of the three-point test. The plot shows the instance of 6 mm deflection which the physical tests showed to be the flexural extension at yield.

## 5.4 Cost analysis

The FR beam structures can be considered an enabler of lightweighting in the proposed upper-deck solution. Achieving a cost feasible solution was considered more critical to the project's realisation rather than designing the optimum lightweight beam structure which would have a prohibitively expensive cost. The choices of the proposed manufacturing system as well as the materials were all intended to achieve this compromise. The manufacturing demonstrator work package detailed in section 5.2 enabled the development of a cost analysis of the proposed curved beam structures.

### 5.4.1 Analysis of production volumes

A factor with significant impact on the choice of braiding and fibre-matrix consolidation techniques is the forecast production volume. The proposed roof structure would require

16 beams per bus. Three different production scenarios were considered with the following production volume estimates:

- Prototype production run: up to 5 buses [up to 80 beams (one-off)]
- Niche market application: up to 20 buses [up to 320 beams/year]
- Full roll-out annual volume: 500 buses [8000 beams/year]

The first stage in implementing the proposed upper-deck structure would be an initial prototype production run of a few vehicles, typically three to five buses which would allow ADL to gain the required installation and in-service knowledge and experience before fully adopting the new structure. Secondly, following a successful evaluation, the concept would be implemented onto production buses. In a scenario where the performance of the structure would be successful but the cost too prohibitive to implement over the whole production, the structure could be offered to a niche market. Niche markets such as tourist buses are typically willing to pay a premium for the additional benefits. The ideal scenario would be that the cost of the structure would enable the concept to be implemented on standard production bus models.

The prototype and niche market scenarios would necessitate low tooling and set-up investments due to the very low volumes. Yet, if the concept is adapted, production volumes of up to 30 beams per day would be required. As detailed in section 5.2, prototype components could be manufactured using a simple passive heating tool. In order to deliver higher volumes, multiple passive heating tools could be used, or else investment in an advanced rapid active heating tool would be necessary.

### 5.4.2 Component cost estimate

This section presented details of the different cost elements that compose the final cost of a braided composite beam structure manufactured using the proposed method.

#### 5.4.2.1 Material cost analysis

- Material cost: £15.50 ± 2/beam

The cost of the commingled yarns (E-glass fibre and PA6) utilised in the project is approximately £7.50 $kg^{-1}$. The estimated weight of the beam with 5 mm wall thickness is 1.87 kg (volume of 0.00101 $m^3$ with a material density of 1866 $kgm^{-3}$). This wall thickness of the beam is a first conservative estimate which will be optimised as detailed design iterations are carried out. A 10% material wastage rate is assumed.

- Silicone bladder cost: £3 ± 2/beam

This is dependent on degree of re-utilisation of bladder.

- Total material cost/beam: £18.50 ± 4/beam

#### 5.4.2.2 Manufacturing cost

- Preform labour cost/beam: £4 ± 2/beam

The cost will vary on the production volumes due to the braiding machine set-up time. The investment required to set-up a braiding unit such as the one utilised for the production detailed in chapter 3.2 is approximately £100,000. Yet, due to the high production output, assuming the braiding set-up is utilised for other projects, the cost incidence on the part is very low.

- Cost incidence due to low-cost tooling option: £0.80/beam

The required tool which would have an approximate size of 1.3 m × 0.45 m would cost approximately £2,000. If the tool is utilised for two cycles daily, an annual output of 500 parts is possible and assuming a five years life for the tool, the incidence on part cost due to tooling is £0.80/part.

- Energy and manufacturing cost: £5/beam

A significant proportion of this cost is based on the energy costs involved in the lengthy oven cure cycle. This could be significantly reduced if multiple tools are manufactured. A projected requirement of 8000 parts per year would require 16 tools which could be simultaneously heated within the oven with the energy and manufacturing costs potentially reduced to £5/beam from £40/beam which would be the case if only one tool is available.

Advanced tooling with active heating and cooling (introduced in section 5.2.3) could be utilised as an alternative to using multiple passive heating tools. A tooling set-up based on the technology developed by SG would cost approximately £50,000 (parametric estimate based on a similar tool). Additionally, a capital investment of approximately £100,000 is necessary to install the required services to operate the tool. This tool should be capable of outputting the required 8000 parts annually, and assuming a tool lifetime of five years, the incidence on part cost due to tooling cost would be £3.75/beam. The more efficient utilisation of heating energy should translate into lower manufacturing costs than is possible with the passive heating costs.

- Finishing cost: £5/beam

This cost related to trimming, finishing and additional operations costs.

### 5.4.2.3 Total part cost

The implementation of a demonstrator programme would necessitate a capital investment of approximately £ 2000 for tool and the cost for each beam costing approximately £60. Considering the full roll-out scenario, assuming the scenario where multiple tools (low-cost passive heating) are utilised simultaneously to achieve the required production volumes (8000 parts annually), the cost of the beam is estimated at £33.50 ± 6/beam. Alternatively rapid active-heating tool could be an option. Initial estimates indicate that at the assumed production volumes, costs would be similar to that of having multiple passive tools. The choice would be guided by more precise forecasted production volumes as well as more accurate tooling and production costs which would be developed during the prototype production programme.

## 5.5 Proposed methodology of braided beam structures design

The manufacturing method that is proposed for the manufacture of curved structural beams consists of a bladder assisted consolidation process of braided commingled FR thermoplastic preforms as illustrated in Figure 5.15.

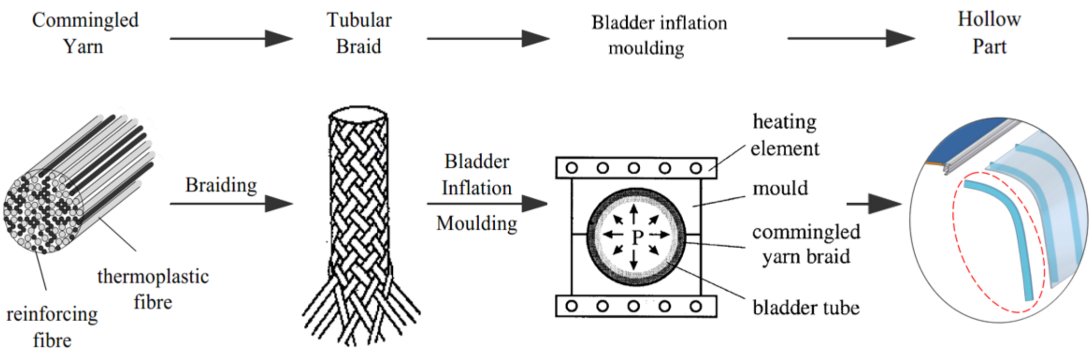


Figure 5.15: The proposed method for manufacture of the curved beams, adopted from [150].

The successful correlation of the FE model (based on the method proposed in section 5.3.3) and the physical testing of the test beams form the basis of a design methodology for braided composite beam structures that could be implemented by ADL. A summary of this proposed model is illustrated in Figure 5.16. The mechanical properties of the braiding yarn constituent materials together with the braiding parameters are utilised to obtain the mechanical properties of the composite material which are in turn used in a macro-FE model of the beam. If the strength or stiffness response of the structure are not sufficient, then either the braiding parameters or the material specifications could be altered until the required performance is obtained.

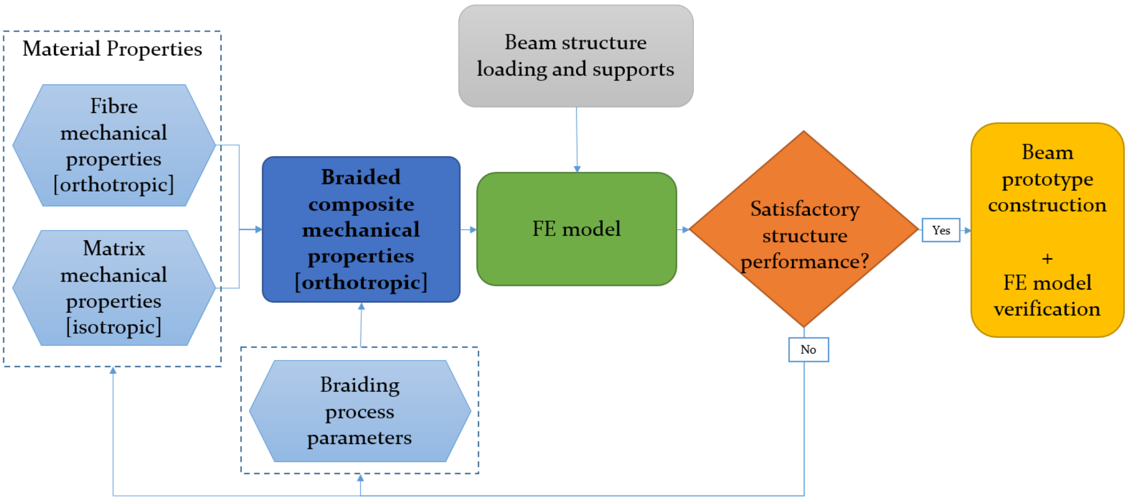


Figure 5.16: Proposed model for development of braided fibre reinforced beam structures.

## 5.5.1 Design validation of proposed upper-deck beam structures

An initial iteration of the proposed methodology was applied to the curved structural beam required for the upper-deck structure in order to assess the validity of the initial weight assumptions presented in section 4.4.

As was detailed in chapter 4, under normal operating conditions, the structural requirements of the upper-deck roof structure are limited to self-support requirements. The roof sandwich panel and additional equipment would impose an average static load of 200 N on each beam. At the extreme dynamic loading scenario defined by ADL as a vertical +3g loading case, a vertical load of 600 N would be experienced by each beam. However, the worst loading case on these beams would be the exceptional scenario of an operator standing on the roof which ADL specifies as load of 1300 N (distributed on an area of 100 mm × 300 mm).

An FE model was created to model this loading scenario with the result illustrated in Figure 5.17. In this maximum loading scenario of a concentrated load of 1.3 kN applied to the top of the beam, the FE model simulated a deflection of 1.7 mm and a maximum von Mises stress loading within the structure of 30 MPa. This stress level is less than 30% of the stresses experienced by the test beams at yield point in the FE model of the three-point bend test (94 MPa as illustrated in Figure 5.14). This indicates that the proposed structure with 5 mm wall thickness is not only structurally sufficient even at this extreme loading scenario, but it could be argued that there is a possibility for further optimisation and lightweighting of the structure. This optimisation should be carried out once further details of the design such as how the beam will be mounted to the structures is defined.

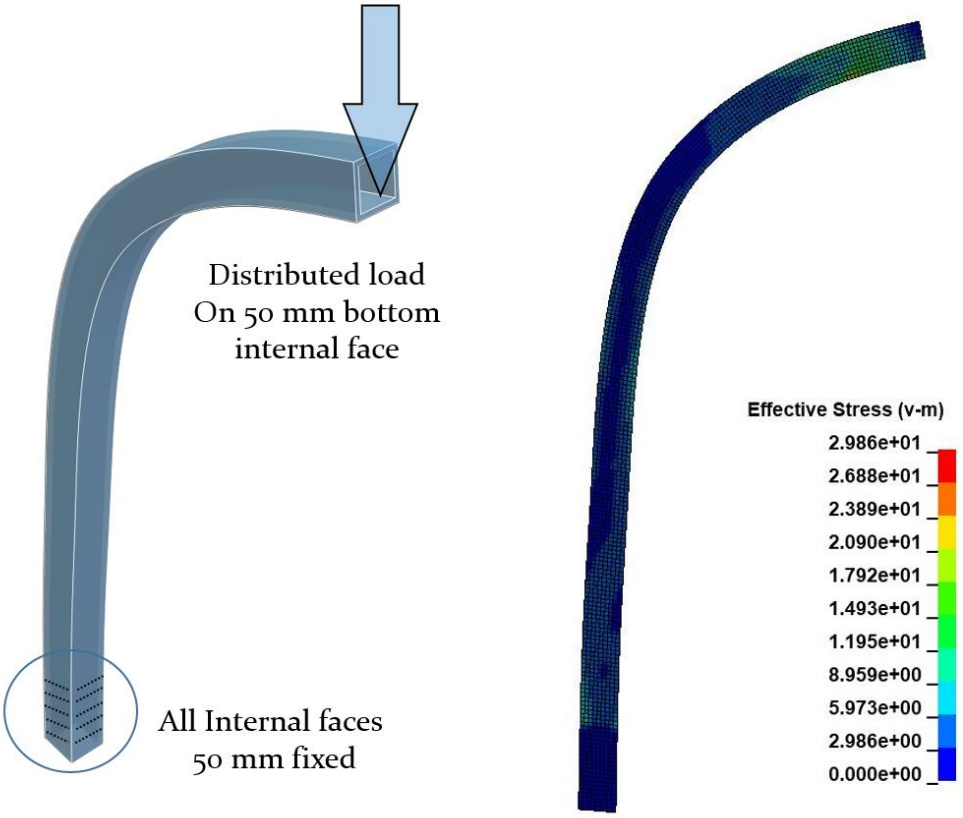


Figure 5.17: FE model of the curved braided beam. The beam was rigidly supported at the bottom end and vertical loading imposed on the top. The maximum loading scenario of 1.3 kN, induces a maximum deflection of 1.7 mm and a maximum von Mises stress of 30 MPa.

## 5.5.2 Conclusions

The scope of this study was to identify a cost-effective solution that would allow the lightweight upper-deck curved beams to be designed and manufactured by ADL. The following were the main outcomes of this study:

- A state-of-the-art review on composite manufacturing technique suitable for the cost-effective production of hollow curved beam structures and the utilisation of braided composite structures within the transportation industry was carried out. The bladder-assisted consolidation of commingled hybrid FR thermoplastic braided preforms was chosen for further investigation.
- A demonstrator production project was carried out in collaboration with a UK based company, Composite Braiding Ltd. Several test-beam structures were manufactured and their bending stiffness measured in three-point bending test.
- A simple FE modelling methodology was set-up in order to model the same three-point bend testing scenario. The FE model was correlated with the physical testing results with acceptable accuracy and hence this FE modelling methodology was proposed as a method for ADL to carry out initial design of similar braided structures.
- A cost analysis of the manufacturing process was carried out, illustrating that the proposed technology is feasible to for both demonstrator component manufacture as well as full production volumes.
- The proposed FE model was utilised to verify the structural strength and stiffness performance of the initial design of the proposed lightweight upper-deck curved beams. It was confirmed that the beams were appropriate although there is scope for further lightweighting potential over the initial proposal.

### 5.5.3 Further applications of braided beam structures

This research programme introduced a cost-feasible composite beam manufacturing technique to ADL. The main motivation for this research was the realisation of the curved beams of the proposed lightweight upper-deck structure, however this technology has the potential of integration into other structures of the bus. The study on lightweight handrail structures carried out by the author, which resulted in the successful production of demonstrator beams illustrated in Figure 5.18, is one such possibility. Braided composite beam structures have the potential of integration into the chassis structure achieving significant lightweighting as was illustrated by two major research projects [151–153]. The successful outcomes of the research addressed one of the main risks identified during the proposal of the upper-deck structure further demonstrating its viability.

Figure 5.18: Curved handrail structures could be feasibly manufactured using braided FR composites.

# 6

# LIGHTWEIGHT POLYCARBONATE GLAZING WITHIN THE BUS INDUSTRY

An integral component of the lightweight upper-deck structure detailed in chapter 4 is the set of curved polycarbonate glazing panels as illustrated in Figure 6.1.

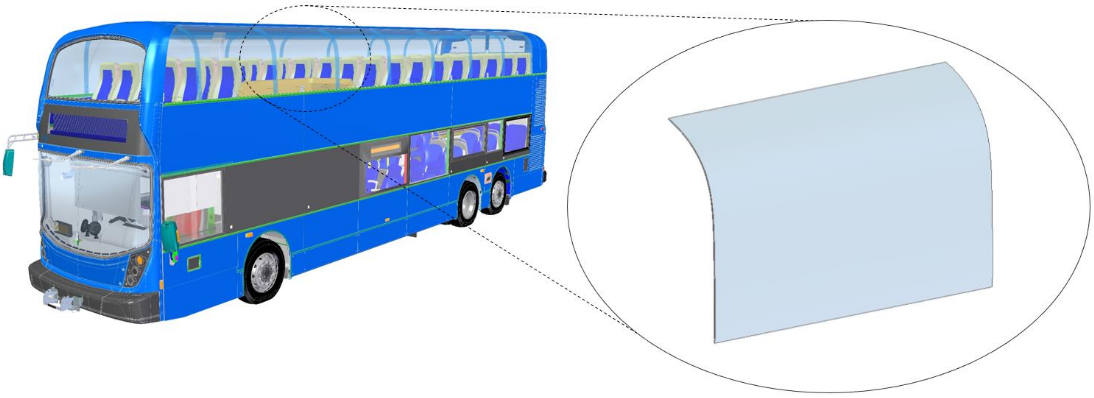


Figure 6.1: Exploded image of a curved polycarbonate glazing panels necessary to realise the proposed lightweight upper-deck structure.

The project risk analysis (carried out at the conclusion of the lightweight upper-deck conceptual design phase) presented in chapter 4, concluded that the successful lifetime performance of the proposed polycarbonate glazing system was one of the primary risks of the project. It was critical to address this risk in order to gain the required confidence in the in-service performance of this technology as well as assess manufacturability and cost aspects of implementing this technology. This chapter summarises two main work packages carried out:

- The application suitability of coated PC glazing within the bus industry was assessed. The state-of-the-art review carried out in collaboration with a leading PC manufacturer identified varies gaps in knowledge that needed to be addressed. The primary focus was the testing of abrasion resistance of PC glazing systems exposed to daily bus-wash equipment. This testing was complemented with fire-exposure performance testing and adhesive compatibility testing.

- Following the successful performance testing work packages, the identified solutions were further verified through a demonstrator implementation programme. PC glazing panels replicating a large complex shaped glass glazing panel currently installed on in-service buses were manufactured to assess aspects of manufacturability and costs. Following installation on in-service buses, the demonstrator panels will provide further verification of the performance forecasting testing previously carried out.

## 6.1 Lightweight glazing: state-of-the-art review

Polycarbonate is a highly durable and impact-resistant thermoplastic. It has characteristics similar to the other widely utilised polymer glazing material, Polymethyl methacrylate (PMMA) also known as acrylic [112]. It is, however, stronger and has superior thermal stability ($T_G$ = 140°C) [154]. Polycarbonate has excellent light transmission properties even exceeding those of many kinds of glasses. Its density is approximately 1200 $kgm^{-3}$, which is 40% that of glass, hence when it is possible to replace a glass glazing panel with PC panel of similar thickness a 60% lightweighting is possible [155].

Whilst the main driver behind the choice of polymer glazing over glass is the lightweighting potential, the choice of PC over PMMA polymer glazing is primarily based on its significantly superior impact strength. PC glazing is considered to be 'virtually unbreakable' having up to 200 times the impact strength of glass and 50 times that of PMMA [110]. One of the legislative mechanical test required as per the *ECE Addendum 42: Regulation No. 43* (R43) safety glazing requirements consists of dropping a steel ball (227±2 g and 38 mm diameter) from a height of 2 m to 5 m depending on the glazing thickness [156]. A satisfactory result is obtained as long as the glazing does not break in separate pieces and the ball does not penetrate the panel. The superior impact performance of PC glazing when compared to PMMA and glass glazing is illustrated in

Figure 6.2. Whilst PC only presents a small dent, PMMA and laminated glass panel both suffer severe damage.

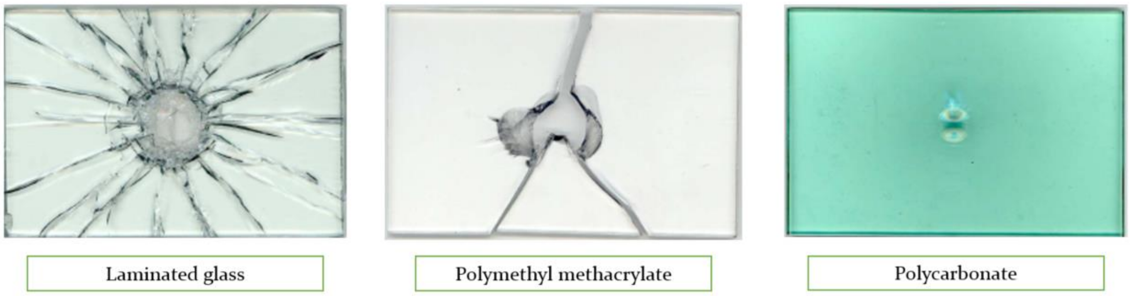


Figure 6.2: Results of R43 drop-ball impact test on glass, PMMA and PC glazing panels, adopted from [91].

### 6.1.1 PC glazing manufacture

There are two main manufacturing methods which are typically utilised to manufacture PC glazing:

- **Injection moulding of final shape parts;** this consists of injecting molten PC resin into a closed multi-sided tool. Once the injected resin cools below the crystallisation temperature, it can be opened and the net-shaped PC component can be released. This method is typically utilised in high volume production of smaller parts (because of high tooling costs) or when the glazing panel has complex geometry. A typical application of this manufacturing technique is the production of car headlamp PC glazing panels.
- **Thermal forming of flat PC sheets;** this manufacturing technique consists of two main steps. A flat PC sheet is extruded in the first step, and if the glazing panels necessitates further form, the PC sheet can be formed in a secondary thermal forming process. This method is typically utilised for low volume production and/or large glazing panels.

### 6.1.2 PC glazing coating technology

Despite the significant advantages PC has over glass, it has a higher rate of in-service degradation and this significant flaw has blocked its market penetration in various instances. The critical mode of degradation is surface scratching, which occurs when exposed to contact with abrasive material. Additionally, PC suffers from physical degradation when exposed to ultraviolet radiation (UV) and to certain chemicals [157].

The poor scratch resistance of PC glazing leads to haze misting of the glazing panel, which severely impacts the optical quality of the glazing panel causing distortion of images, ghost images, glare and reduced visual performance particularly in low lighting conditions. Hence, protective hardcoats critically essential for enabling the use of PC for optical glazing. They extend the long-term exterior durability and performance of polymers by helping them maintain their colour, gloss, light transmission and physical properties while enhancing their weatherability and resistance to abrasion, chemicals and solvents. A review of the various coating systems, which are currently commercially available, is presented in Figure 6.3.

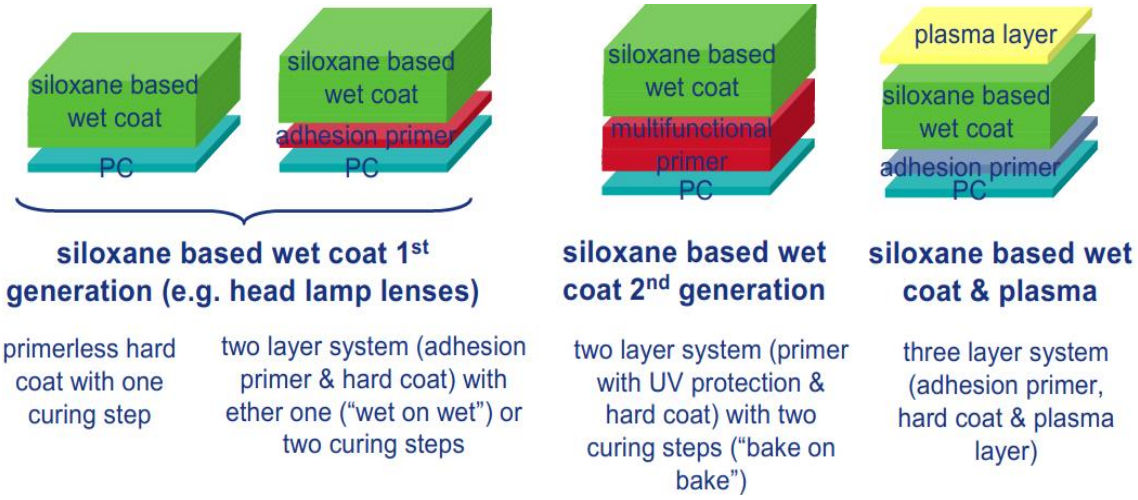


Figure 6.3: Review of different PC glazing coating technologies, adopted from [91].

The first coatings were developed during the 1970's for utilisation in the ophthalmic industry (coating of PC glass lenses) [158]. Thermally cured silicone based abrasion-resistance hardcoats were further developed in the 1980s to augment the performance of PC headlamp lenses. In 1989, 'GE Silicones' introduced the 2-layer system called the AS4000. This coating system had a performance far superior than the SAE J576 automotive headlamp minimum requirements making it the leading coating systems in use for protecting PC headlamps even today [159]. These coating systems have been further developed and enhanced during the last two decades to deliver the 2nd generation wet-coat systems which are currently commercially available.

The PC glazing panel is coated with a thin 1-2 μm layer of acrylic based primer layer (layer-1) which helps the adhesion between the PC substrate and the top hardcoat. Additionally, advanced primer coatings provide UV protection. A siloxane based hardcoat (layer-2) with a thickness of 3 to 12 μm is applied typically utilising a flow coating method [160]. This coating could be further enhanced through the application of a plasma layer on top of the wet-coat. Plasma-coat technology is a glass-like coating applied over the wet-coat, delivering the highest level of resistance to weathering and abrasion which is currently possible. The coating technology, which is more accurately known as plasma-enhanced chemical vapour deposition (plasma CVD), deposits a layer on top of a wet-coat system which protects the same wet-coat layer hence enhancing both the abrasion resistance as well as the durability of the coating.

Literature on in-service performance of PC glazing is limited. In other industries, in-service experience of PC glazing coated with the currently available top performance coatings has shown that successful performance in excess of ten years is possible. The confidence in these glazing systems has considerably increased in the recent years and companies such as Sabic are offering limited commercial warranty cover of up to ten years on such glazing systems [161].

## 6.1.3 Polycarbonate glazing optical properties

The level of transparency and optical quality are critical aspects of glazing and are defined as a ‘principal characteristics’ of the glazing panel within regulatory legislation [156]. The optical quality of a PC glazing will depend on the extent of optical distortions and visual defects which are dependent on the quality of the PC and manufacturing process.

### 6.1.3.1 Optical distortions

Optical defects in a glazing panel change the appearance of an object viewed through the glazing panel and are caused by different types of shape variations which could occur within the glazing panel such as illustrated in Figure 6.4. Glazing panels which are necessary for the safe operation of the vehicle (visibility by the driver) have specific optical distortion requirements set by R43 [156].

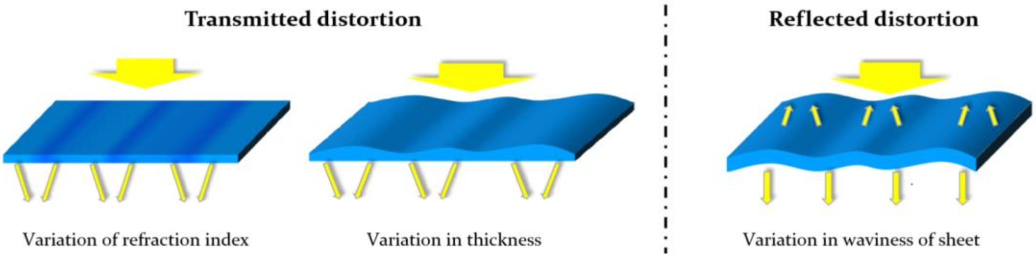


Figure 6.4: Optical distortions caused be various types of defects within the glazing panel.

### 6.1.3.2 Visual defects

The second type of optical defects are visual optical defects. These could be either embedded within the core or on the surface of the glazing panel surface and include:

- Gels (un-molten PC) or black specs (burned PC)
- Inclusions (foreign particles), air bubbles or fibres
- Surface contaminants and coating defects

These defects can be caused either during the manufacture of the glazing panels or during the lifetime of the glazing panel and interfere with the transmission of light through the glazing panel hence modifying the optical quality of the panel. The optical effect of these defects can be measured by quantifying two properties, the transmittance and the amount of scattering of light as illustrated in Figure 6.5.

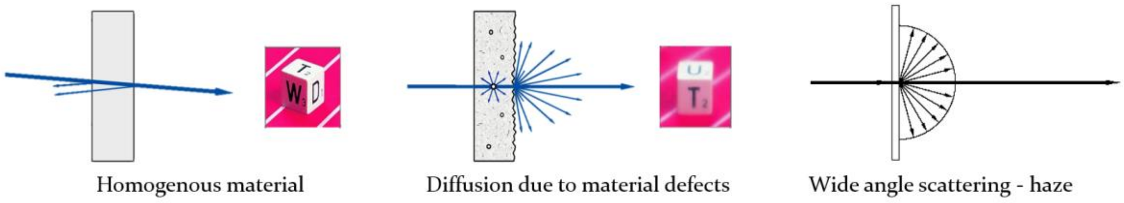


Figure 6.5: Light transmission through an ideal homogenous material and diffusion causes by internal and surface structures. Haze refers to wide angle scattering, adopted from [162].

## 6.1.4 Measuring the optical quality of a glazing panel

Haze is a measure of the wide angle scattering and is widely used within legislation as a measure of the optical quality of glazing panels. The measurement of haze is defined in the standard ‘ASTM D1003-00’ and is carried out utilising a haze meter [162]. The measurement principle of the haze meter is illustrated in Figure 6.6. A beam of light passes through the specimen and enters an integrating sphere. The sphere’s interior surface is coated uniformly with a matte white material to allow diffusion. A detector in the sphere measures total transmittance (direct transmittance plus diffuse transmittance) and transmission haze. A ring sensor mounted at the exit port of the sphere detects narrow angle scattered light (clarity) hence allowing for the haze measurement to be extrapolated from the clarity and total transmittance measurements [163].

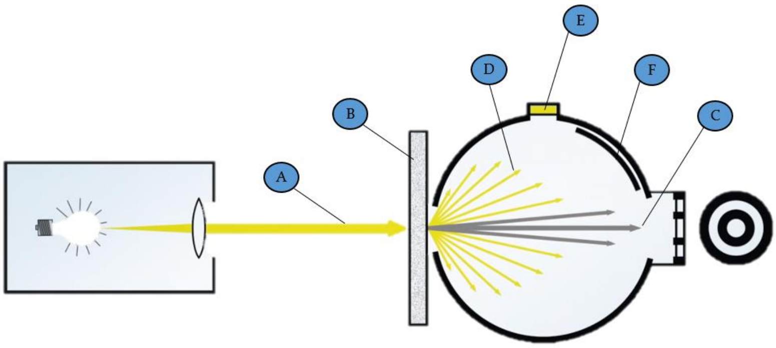


Figure 6.6: The haze meters measurement principle. An incident beam of light (A) is transmitted through the test panel (B) into an integrating sphere. A detector (E) can measure the total transmittance, whilst a trapdoor (F) allows the narrow convergence light (C) to be caught within a light box in which a sensor can take the panel's 'clarity' reading. The panel's haze reading due to the wide angle scattered beams (D) can then be calculated, adopted from [163].

### 6.1.5 Review of relative legislation

Glazing for automotive vehicles including buses are subject to type-approval as glazing is considered a safety-relevant system. The necessary tests in order to achieve approval are set by standards which every country adopts. The three main standards are the European *ECE Regulation No. 43* [164], Japan Safety Regulations for Road Vehicles Article 29 and the USA ANSI Z26.1a-1980 FMVSS 205 [165]. The approval procedures are very similar [112]. The regulations allow for polycarbonate glazing to be utilised everywhere on the bus except for the windshield and the windows to the immediate left and right of the driver as these are classed as glazing required for operator driving visibility. These require a very restrictive abrasion resistance specifying less than 2% haze after 1000 Taber™ Abrader cycles [166] which most current coating system are not able to achieve.

Legislative bodies around the world are currently discussing and proposing legislation that could see a significant change in bus glazing systems with polycarbonate glazing possibly becoming the predominant lightweight glazing system. Toughened glass glazing panels which are currently the main glazing option offer very limited resistance to impact, and in the event of a serious accident, such as a rollover, passengers could be thrown out of the windows. In light of this, the US National Highway Traffic Safety Administration (NHTSA) proposed a new Federal Motor Vehicle Safety Standard (FMVSS) No. 217a, 'Anti-ejection glazing for bus portals', in 2016 [111]. This would necessitate the utilisation of advanced glazing systems that would be able to retain a 26 kg load impacting the glazing panel at

21.6 m/h, a test carried out to simulate the impact of a person onto the window in a bus rollover situation.

### 6.1.6 Conclusions of state-of-the-art review

As was introduced in section 2.5.4.3, PC glazing is successfully being introduced into various transportation industries. The one significant key advantage that PC has over both glass and PMMA glazing is its superior impact resistance. In applications where this characteristic is essential to ensure operational safety, PC glazing is the lightweight glazing option of choice in spite of its main drawback which is its poor scratch resistance.

Additionally, PC glazing could offer other advantages which in particular applications could further justify the increased cost of PC glazing compared to glass. The salient three properties include the lightweighting potential, increased thermal conductivity resistance and design flexibility. PC glazing has the potential to offer improved performance when its utilisation is correctly integrated into the system's design ensuring that the potential benefits are fully exploited.

Successful in-field applications of advanced coated PC glazing, in various industries and operational conditions, illustrate that PC glazing is capable of meeting stringent requirements set by both legislative bodies and OEMs. Still, it is evident that the durability of the glazing solution is dependent on the specific application. Hence, specific exposure conditions when introducing PC glazing into a new application need to be carefully analysed, and if necessary testing carried out to ensure that the required performance is offered by the particular PC glazing system that is being proposed.

## 6.2 Accelerated lifetime abrasion resistance testing of PC glazing

Glazing on buses is exposed to very similar environmental conditions as other road vehicles and as identified in the state-of-the-art review there are several successful commercial applications of PC glazing within the transport industry as introduced in section 2.5.4.3. However, the majority of bus operators across the UK wash their buses daily with partially automated bus washing equipment which exposes bus exterior panels to a more severe and much more frequent abrasive environment than the average vehicle. In addition, aggressive alkaline cleaning solutions are utilised in order to help degrease and clean the surfaces. As such, any material installed on the exterior of a bus must be able to resist these daily washing regimes. The state-of-the-art review concluded that there is insufficient knowledge on the performance of coated PC glazing exposed to these specific conditions. Hence a research programme was set-up intended to answer the question: 'Will a currently available, economically feasible coated PC glazing system be able to survive the very aggressive daily bus washing process for the typical lifetime of a bus?'

The following are the three main steps of the research methodology that was adopted:

1. A state-of-the-art review of abrasion resistance forecasting methods.
2. Analysis of bus washing practice and procedures in order to identify a suitable testing method.
3. Testing of PC glazing coated with various coating systems in order to identify if any commercially available coated PC glazing which would be able to optically survive these particular abrasive conditions.

### 6.2.1 A review of abrasion-resistance forecasting methods

A review of methods that are currently used in order to assess the abrasion resistance of glazing materials was carried out to identify if existing testing methods could replicate the exposure conditions as well as the total exposure duration that a bus glazing panel would typically experience during its lifetime.

The Taber™ test method as defined in the ASTM standard 4060 [167], is a widely used and accepted method for evaluating the resistance of surfaces to rubbing abrasion [168]. The test is an abrasion behaviour forecasting test intending to forecast how a material will behave in a 'high wear environment'. In this test, two abrasive wheels (compacted silica carbide granules) rotate freely in opposite directions and are pushed with a specified load against the test-sample for a specific number of rotations. Haze measurements are taken before and after the abrasion exposure and the test-glazing achieves legislative certification if the change in haze is below a specified limit [169].

In spite of the wide spread utilisation of the Taber™ test, this methodology has several drawbacks. One of the primary drawbacks of the test is its poor repeatability [170]. Whilst evaluating these repeatability issues, a study concluded that the Taber™ test is unsuitable to characterise abrasion resistance of automotive glazing (in particular coated polymer glazing) due to its crossed-scratch abrasion pattern mechanism which does not effectively and realistically replicate in-service wear conditions [168].

In order to address this deficiency of the Taber™ test in relation to polymer glazing, the Informal Group on Plastic Glazing (IGPG) as approved by the UN Working Party on General Safety Provisions (GRSG) reviewed several abrasion testing procedures over a number of years, following which in 2015 successfully added an amendment to R43 allowing for an alternative abrasion testing solution which could be utilised as an alternative to Taber™ test for certification of polymer glazing [156]:

- A windscreen wiper test simulating the abrasive effects of the windscreen wipers on the glazing panel [171].
- A sand drop test simulating the abrasive effects of dust and sand hitting the glazing panel [172].
- A laboratory car wash test simulating the abrasive effects of car wash brushes on the glazing panel [173].

Out of the three tests, an adaptation of the laboratory car wash test would have been the most suitable set-up to simulate the effects of the bus washing environment. The standard test could be extended in order to simulate the significantly increased exposure a bus experiences in its lifetime when compared to a car. More realistic testing could be achieved through a set-up similar to that used in two separate tests run by Bayer AG (set-up illustrated in Figure 6.7) [91] and General Motors [174]. Test glazing PC having different types of coatings were attached to the roof top of a car. The car was exposed to normal operation road conditions and once a week washed within a carwash as illustrated in Figure 6.7. Haze measurements of the panels were taken following 50 and 150 wash cycles (equivalent to approximately one year and three years of operation) and results are shown in Figure 6.7 [91]. The test concluded that PC coated with a siloxane-based wet-coat successfully passed the test with no visible haze detected at the end of the long-term exposure test. The test also showed issues with plasma coated panels which suffered early failure even though as detailed earlier plasma coated panels have the best performance in the Taber™ test. This result illustrated the importance of testing these glazing panels within an environment that accurately replicates in-service operation conditions.

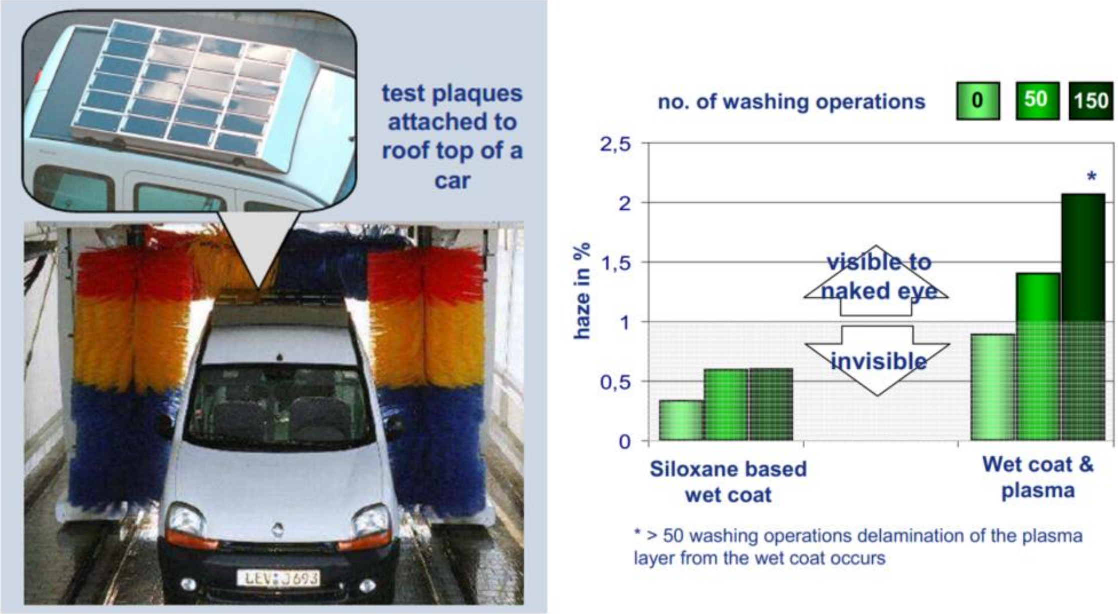


Figure 6.7: Set-up and results of real car wash abrasion testing. Positive results achieved by siloxane based 2-layer hardcoat system with no visible haze detected after long term exposure tests, adopted from [91].

Hence, it was concluded that the ideal set-up in order to test prospective panels in the most realistic conditions would be to carry out repeated testing of panels within an actual bus-wash, up to a total duration a typical bus would experience throughout its lifetime. These extended tests carried out in industry-specific exposure conditions would add valuable knowledge to what is currently available.

### 6.2.2 Aim of the testing

The primary aim of this testing work package was to expose samples of PC glazing panels with a variety of coatings to equivalent abrasive conditions as those that would be experienced by a bus during the bus-wash cycle. Additionally, the coated PC panels should withstand repeated exposure to a duration equivalent to an average bus lifetime. For the scope of this study, this was defined as twelve years and a worst case scenario of one wash per day is assumed (i.e. a total of 4,380 cycles).

### 6.2.3 Bus washing procedures

There are two main types of bus washing set-ups installed at bus depots where buses tend to be washed daily; fully automatic and drive-through units. The drive-through version consists of a stationary bus-wash set-up through which the bus is driven at slow speed between rotating brushes, which wash the bus exterior. In the fully automated bus-wash, the bus is driven to a predetermined stop and parked. The bus-wash structure then moves the rotating brushes along the length of the bus as per a predetermined programme. This ensures a thorough and consistent wash quality which is sometimes lacking in the case of a drive-through where the wash quality is dependent on driving the bus at an appropriately low speed.

A bus depot equipped with fully automatic bus washing systems was chosen as this set-up offers two distinct advantages over the more predominant drive-through bus washing systems:

1. Given that every bus-wash cycle is fully automatic, it was possible to plan and precisely control the experiments.
2. These types of bus-washes typically expose the buses to a longer wash cycle and as such, (for the scope of these experiments) one could conclude that the PC panels are being exposed to a worst-case scenario testing environment.

### 6.2.4 Testing method proposal

The initial plan for the testing was to have a set-up similar to the tests carried out by Bayer AG as was illustrated in Figure 6.7. Two test variations were originally considered:

- Fixing of PC sample panels onto the exterior body of an in-service bus. This would be the ideal testing scenario but this set-up fails to achieve the requirement of carrying out accelerated testing to expose the panels to a lifetime equivalent exposure.
- Repeated cycling of the bus-wash operation on the same bus. This set-up could satisfy the requirement of the test to expose the test panel to a lifetime equivalent exposure. Two main drawbacks were identified. Firstly and most critically, the panels would be continuously in a ‘clean’ condition which does not replicate typical operating conditions, where the bus surfaces are covered by a mix of dust and pollutant. Additionally, 4,380 wash cycles equivalent to 365 hours of operation of the bus-wash would be necessary.

During detailed evaluation of the bus-wash set-up and operation, an innovative concept for carrying out the testing was identified. The proposal consisted of creating a fixture that would enable test panels to be continuously exposed to bus-wash brushes whenever the bus-wash is in operation as illustrated in Figure 6.8. Given that the bus-wash would be utilised in normal operating conditions, the test panels would be exposed to the same 'dirty' water coming off the bus surfaces. By setting the panels at the same distance from the brushes as the bus surfaces are, the panels would be constantly exposed to practically identical abrasive conditions. Additionally, this set-up would offer the opportunity of accelerated testing as the test panels would be under exposure for a significant part of the wash cycle, whilst any part of the bus is only in contact for a few seconds. Hence, during each complete bus-wash cycle, the test panels would be exposed to the equivalent exposure of multiple bus-washes. Finally, excluding set-up costs, the tests were carried out at no cost and no dedicated energy and water expenditure.

Figure 6.8: Proposal of testing concept: Test samples to be mounted onto a purpose built frame that would allow the test samples to be exposed to the bus-wash brushes whenever the bus-wash is in operation.

## 6.2.5 Testing apparatus and set-up

The initial stage of this test consisted of the design and manufacture of a frame that would allow the test panel to be mounted safely and securely at a precise location in relation to the brushes. Following identification of feasible mounting points on the bus-wash brush moving frame structure, a frame as illustrated in Figure 6.9 was designed. The frame was manufactured utilising standard 45 mm aluminium profiles and connectors from the Bosch Rexroth range [175]. The mounting arms of the frame were designed to be adjustable so that during installation the exact distance between the test samples and the brushes could be set-up to ensure the panels experience the same brush washing pressure as the rest of the bus exterior panels. The size of the frame allows 20 test samples (290 mm x 70 mm) to be mounted so that repeated samples of various coatings could be tested simultaneously.

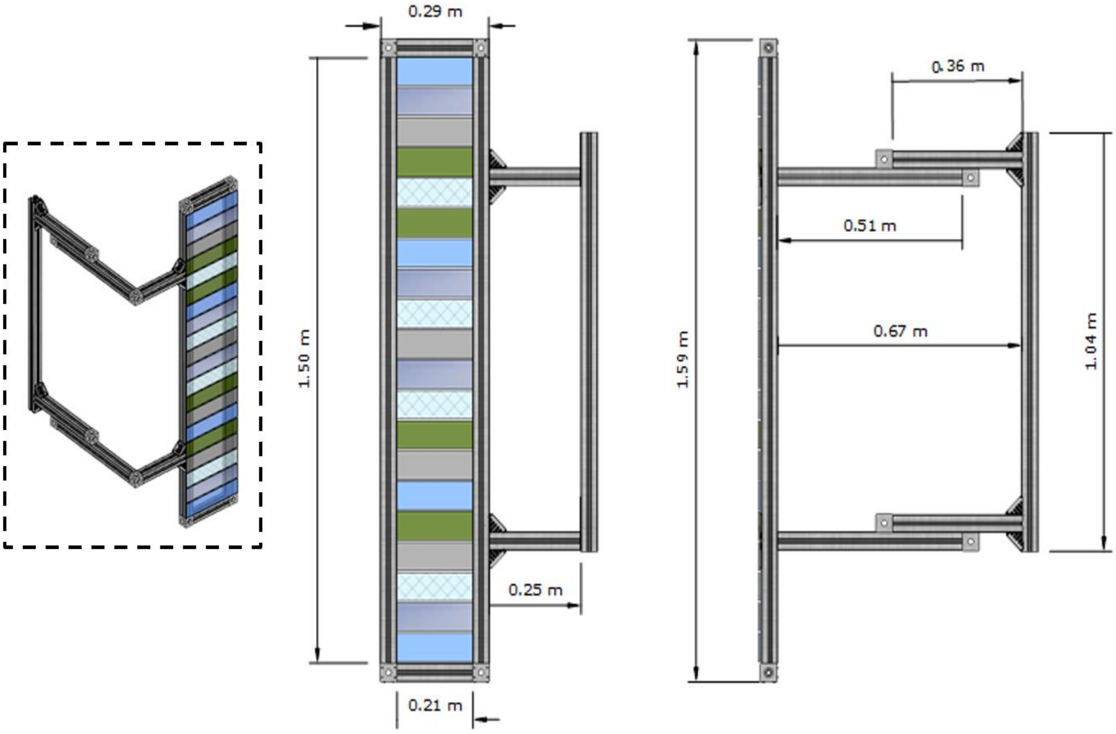


Figure 6.9: Details of the frame constructed to mount test panels onto the bus-wash structure.

## 6.2.6 Testing procedure

The testing procedure is detailed below and follows the principles of other standard abrasion resistance forecasting methods as detailed in section 6.2.1

- Haze measurement of un-exposed test-panels.
- Sample mounting onto test-frame.
- Exposure to bus-wash operation to a specific cycle count.
- Removal of samples and cleaning (multistep nonabrasive process consisting of washing with running water, drying, wiping with an iso-propanol soaked soft cloth, followed by deionized water and drying).
- Analysis of effect of bus-was exposure – haze measurement.

The haze of the polycarbonate panels was measured using a haze meter, the BYK-Gardner Haze Gard plus[163]. The testing procedure consists of holding the test sample in front of the appropriate port and on actuation, the equipment will transmit light through the panel and in a few seconds the haze measurement is given on the output screen.

### 6.2.7 Calculation of equivalent abrasion exposure time

The proposed test set-up allowed accelerated testing as during a whole wash cycle, the test panels were in contact for 120 seconds out of a 200 second cycle compared to approximately 4 seconds for any particular section of the bus. Hence, during one wash cycle, the test panels are experiencing the equivalent total contact time of 22 wash cycles. At the Reading Buses depot where these tests took place, an average of 65 buses are washed daily in a single bus-wash, hence during 24 hours of normal bus depot operation, the test samples would experience exposure equivalent to approximately four years.

### 6.2.8 Testing operations

The testing operation was organised into three phases:

- Testing phase #1: Verification of equipment set-up and correct exposure of panels.
- Testing phase #2: Lifetime equivalent exposure of different coated PC sample panels
- Testing phase #3: Testing of performance of adhesive films on PC glazing exposed to bus-wash conditions.

#### 6.2.8.1 Testing phase #1: Test verification

The scope of the first testing phase was to validate the proposed testing set-up. Primarily, it was necessary to ensure that the frame would not hinder the normal operation of the bus-wash. Additionally, the correct positioning of the frame with regards to the brushes as well as the precise contact time of the brushes and the test panels during one cycle needed to be confirmed. During this first testing trial, twelve test samples of uncoated PC panels were mounted onto the frame as illustrated in Figure 6.10. The test successfully demonstrated the correct positioning of the test samples and the bus-wash automatic operation was not hindered in any way.

Figure 6.10: Frame with test samples mounted on the bus-wash at Reading buses depot. Left and middle: Side view of the frame with the test panels mounted. Right: Test samples exposed to the brush washing action whilst a bus is undergoing the automatic wash cycle.

Following the initial verification cycles, the twelve uncoated PC panels were exposed to an equivalent 2.4 years of bus operation. Following cleaning of the samples, measurements of the haze were made and the results are presented in Figure 6.11. The most important result of these tests was the clear abrasive effect the bus washing cycles had on uncoated PC. The median haze value increased from 1.14 % prior of the exposure to 11.35 % following the exposure.

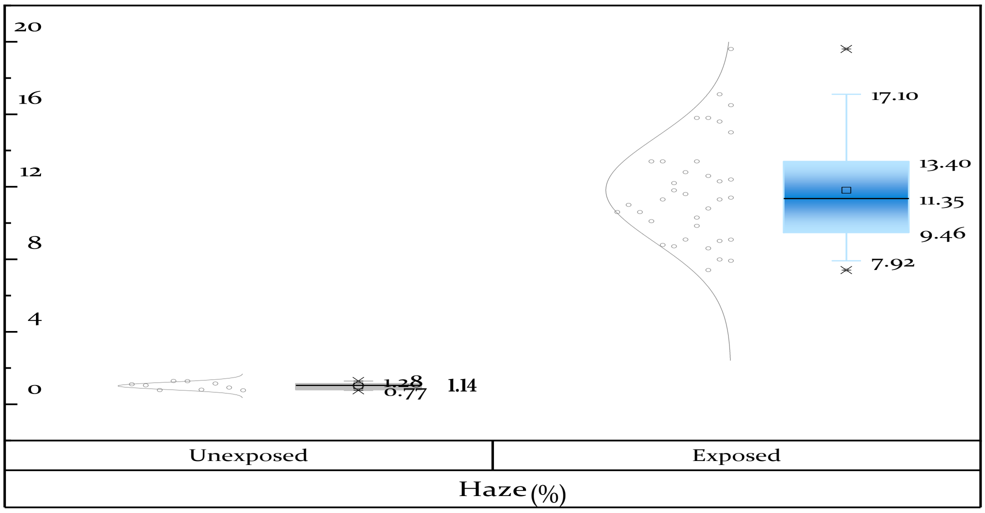


Figure 6.11: Results of the first testing phase: Changes in haze of twelve samples of uncoated PC.

#### 6.2.8.2 Testing phase #2: Lifetime equivalent abrasion testing

Following further detailed discussions with Sabic, three different coatings were shortlisted for testing:

- MR5E coating which is a last generation 2-layer wet-coat system (MR5E is a Sabic tradename for the coated sheets they manufacture using the Momentive™ AS4000 coating system).
- FMR5XT coating is a modified, softer version of the MR5E which allows coated flat sheets to be cold formed into shape. This is not possible with the MR5E coating.
- Experimental coating which was in development stages at Sabic.

All the above coatings are siloxane based wet coating systems as introduced in section 6.1.2. The coatings are 2-layer systems consisting of a primer with integrated UV protection and a hard top-coat. In addition, two control test panels (one uncoated PC and one toughened glass) were added. Four repeats of each test panel type were randomly allocated and mounted onto the test frame as illustrated in Figure 6.12.

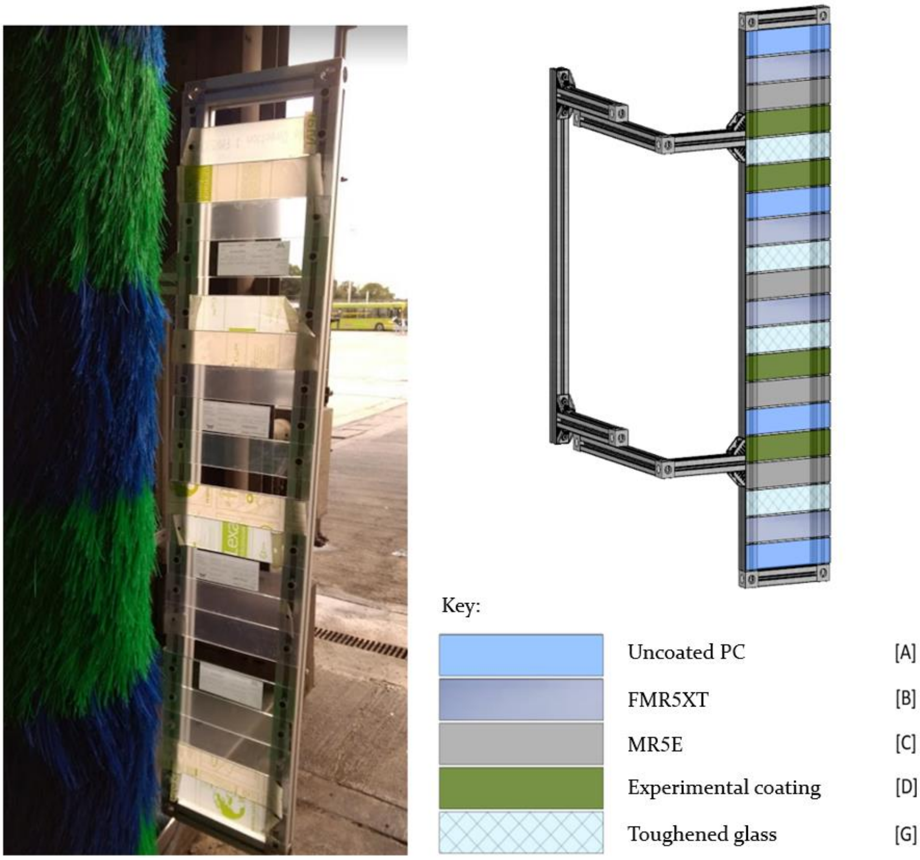


Figure 6.12: Set-up for the main testing phase. Four repeats of three different coated PC panels, an uncoated PC panel and a control glass panel were randomly placed on the frame.

The main results of the 12-years equivalent exposure are illustrated in Figure 6.13. Following the exposure, one of the coatings (MR5E) had a final haze reading similar to that of the glass control panel. Although the performance of the two other coatings was significantly better than that of the uncoated PC, surface scratching visible to the naked eye was observable after the tests.

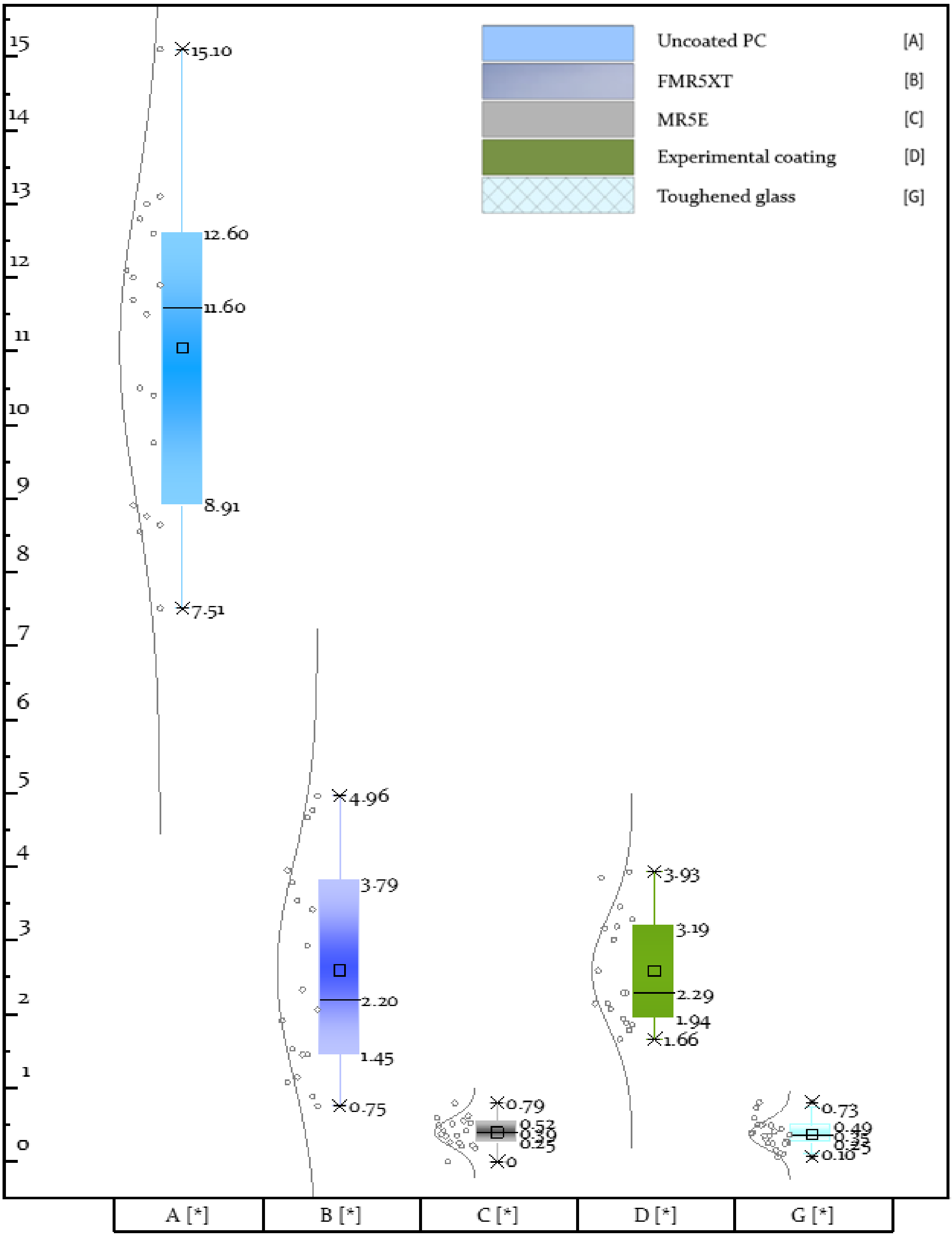


Figure 6.13: Percentage haze measurements of the five different panels following 12-year equivalent exposure to the bus washing environment.

A detailed comparison of the best performing coating (MR5E) and glass is presented in Figure 6.14. It could be noted that even though the PC panel did suffer some deterioration compared to the original state, the final haze measurement following the exposure is statistically equivalent to that of glass. These positive results are in line with the results of the car wash testing carried out by Bayer AG as detailed in section 3.2.5.

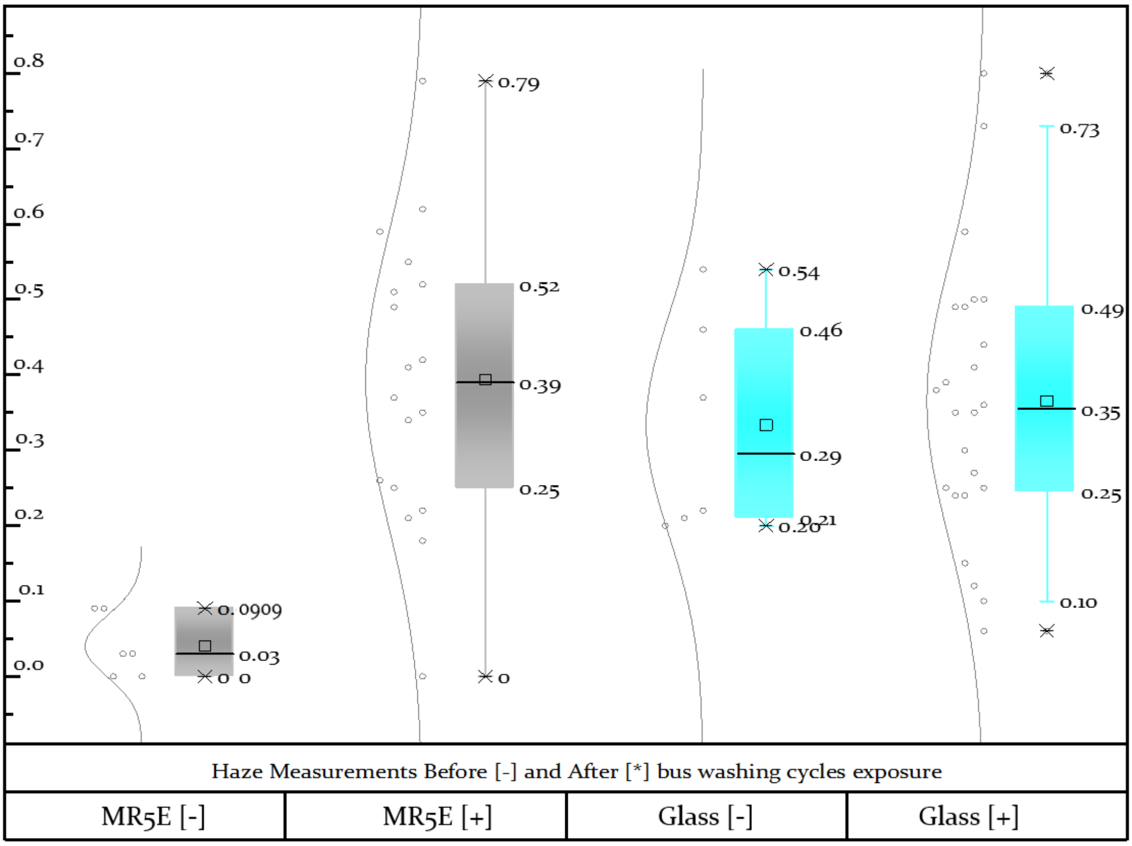


Figure 6.14: A comparison of the percentage haze measurements before and after the 12-years equivalent exposure of MR5E coated PC and toughened glass.

### 6.2.8.3 Testing phase #3: Adhesion performance of marketing films

Following the positive results of the testing carried out in phase #2, a final set of tests was carried out to assess an additional performance aspect. It is becoming increasingly common within the bus industry to cover the exterior of a bus with printable adhesive films. Although the performance of such adhesive films on glass is well known, there is limited information on in-field performance of such adhesive films attached to PC glazing. Hence, it was an opportunity to utilise the bus-washing exposure set-up to test the behaviour of such films bonded onto coated PC glazing. Various types of adhesive films manufactured by market leader 3M Company [176] were bonded onto MR5E PC panels and mounted onto the exposure frame as previously detailed. These films are replaced at the end of a marketing campaign which typically run for up to six months, hence these panels were exposed to an equivalent of one year exposure. The results were positive as no delamination of the films was visually observed on any of the test panels as shown in Figure 6.15.

Figure 6.15: Right: the utilisation of see-through adhesive films on buses. PC panels covered with adhesive films – before (middle) and after (right) the bus-wash exposure testing.

### 6.2.9 Analysis of test results

The following are the main conclusions of the abrasion-resistance forecasting work package that was carried out:

- The state-of-the-art review on currently available abrasion-resistance forecasting techniques illustrated that available testing methods and/or available results are not suitable for giving the specific knowledge needed for the lifetime abrasion performance forecast of coated PC glazing relevant to the bus industry.
- An innovative abrasion resistance-testing set-up was proposed, designed and successfully implemented to be able to expose potential glazing panels to realistic bus-wash exposure conditions for controlled duration which could be equated to a specific duration of bus lifetime.
- A specific coating solution (Momentive™ AS4000 two-layer wet-coat system (MR5E)) that will survive the abrasive effect of bus washing was successfully identified.
- The testing carried out considered worst case scenarios further increasing robustness of results achieved.
- The results obtained were in line with results obtained from similar testing done within the automotive industries by GM and Bayer AG.

The testing that was carried out has some limitations which need to be considered:

- Secondary effects such as UV, chemical and water exposure could have an ageing effect on the coating, which could result in a different abrasion resistance.
- The test panels were set at a specified distance away from the centre of the washing brushes as recommended by the manufacturers. However, as the brushes move along the bus, different bus surfaces may be exposed to abnormal, concentrated, higher washing pressure at specific points.
- Another factor which could affect the glazing abrasion is the state of wear of brushes. The bus-wash brush manufacturers recommend that the brushes are replaced once they start having sharp split ends. The brushes that were utilised for this testing were still within the recommended operating period.

## 6.3 Adhesive bonding of PC glazing

The proposed assembly method for the PC glazing panels under investigation is adhesive bonding. Any adhesive that would be utilised to bond PC glazing would need to be flexible in order to accommodate thermal expansion of the panels. In addition, it must be chemically compatible with PC. It is important that the glazing panels are free of residual stresses as thermoplastics are prone to environmental stress cracking (annealing is necessary during the thermoforming process). Stressing of the panel due to the bonding needs to be avoided. Additionally, bond lines and uncoated edges of the PC glazing sheet need to be protected in order to ensure durability of the bond and glazing panel.

Testing on compatible adhesives was carried out in collaboration with Sika AG, Switzerland [177]. The scope of the tests was to identify an adhesive which could achieve a structural bond without having to mechanically remove the coating. Two adhesive types which are chemically compatible with PC were identified. One is a polyurethane (PUR) and the other is a silane-terminated-polymer (STP) based adhesive. It was concluded that an STP adhesive (SIKAFLEX®-558 [178]) could be used without the requirement for mechanical preparation. A simple cleaning or surface activation step is sufficient to achieve the required adhesion. Various PUR adhesives could also be utilised but in this case the application of a primer (SikaQuick®-506 FG primer) is necessary in order to achieve good adhesion. Further analysis of the specific glazing panel would dictate the best suited adhesive for the particular application.

## 6.4 Fire-exposure performance of PC glazing

The UN regulation *ECE Addendum 117: Regulation no. 118* (R118) defines the acceptable burning behaviour (ignitibility, burning rate and melting behaviour) of materials utilised for the construction of buses (category M3 vehicles of classes II and III) [121]. The regulation specifies that any materials installed more than 500 mm above seat cushions and in the roof need to undergo the melting behaviour test (specified in Annex 7 of R118). In addition, any materials installed in a vertical position within the interior component need to pass the vertical burn test (specified in Annex 8 of R118). Following the successful bus-wash abrasion testing, in collaboration with Sabic, PC glazing panels (4 mm and 6 mm) coated with AS4000 2-layer coat were exposed to the 'drip test' and 'vertical burn test' as illustrated in Figure 6.16.

During the 'drip test', an electric radiator emits 3 W/cm$^2$ on the sample which is supported on a metal grill. During a ten minutes exposure the following need to be recorded: whether any drops fall from the materials, whether these drops were flaming, and if the cotton wool in the bottom tray ignites. A successful result is obtained as long as any drops do not cause the cotton wool to catch fire, and in this case no drops were released from the sheet. During the 'vertical burn test', samples of the material are vertically exposed to a flame and the speed of propagation of the flame over the material is analysed. The vertical burn rate needs to be less than 100 mm/minute or the flame must extinguish before the first marker thread is destroyed in order for the material to pass the test. In this case, the PC panel self-extinguished. It could be concluded that all the specimens successfully and robustly passed both tests.

Figure 6.16: Left: Drip-test being carried out on coated PC samples. Right: Results of the vertical burn test. All tested specimens successfully and robustly passed the tests. Tests carried out as specified by Annex 7 and 8 of ECE Add.117, R118 [121].

## 6.5 Development of a demonstrator lightweight glazing panel

Following the positive results obtained from the bus-wash exposure testing, a project was set up to develop a one-to-one replacement for a glass glazing panel currently installed on a production bus. The aims of this project were twofold. Firstly, a number of glazing panels would be installed on in-service buses, hence serving as an extension to the testing that was carried out further verifying the test results. Secondly, an analysis of the manufacturing process would yield design guidelines to support future PC glazing projects within the bus and wider mass-transit industries.

The panel that was chosen for this case-study was the rear panoramic window that is installed on ADL's two-axle DD bus; the Enviro400 City variant [179] which is illustrated in Figure 6.17. The panel is a 3D curved glazing panel, manufactured out of laminated glass panel (two layers of glass with a polymer mid-layer) with a total thickness of 6.7 mm and weighs approximately 21.7 kg.

This demonstrator manufacture project was set up and managed by the author in collaboration with Sabic [180] and an EU market leading tier 1 manufacturer specialising in the manufacture of coated polymer glazing components.

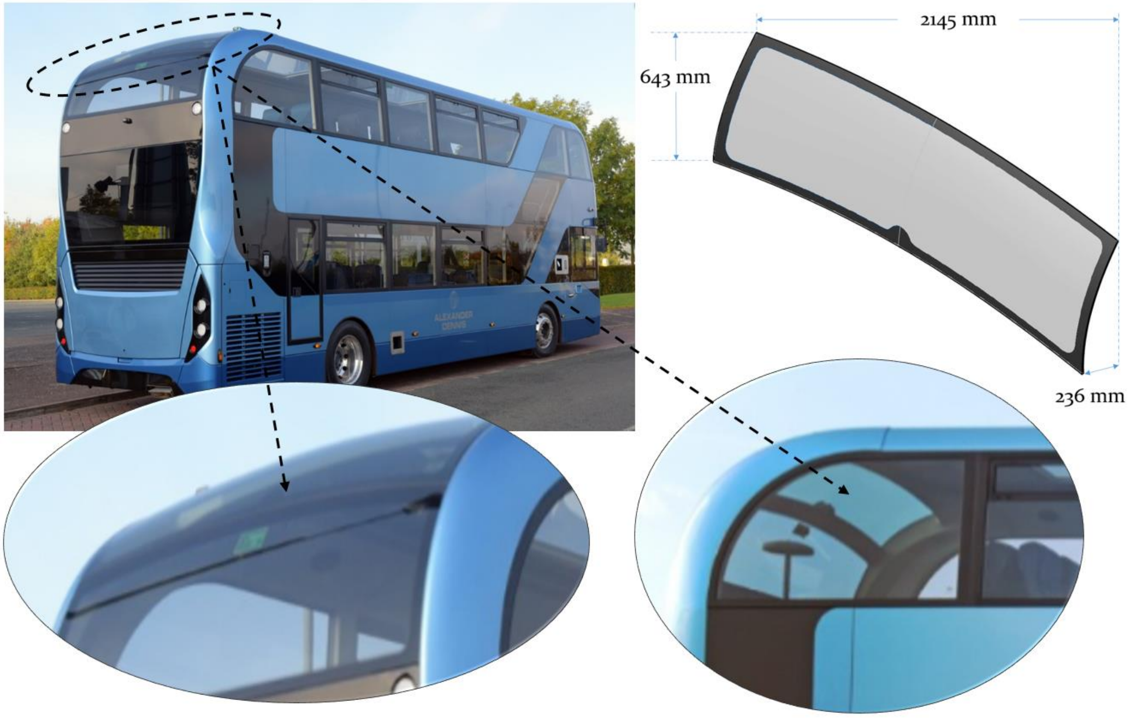


Figure 6.17: The rear panoramic upper-deck window of the Enviro400 City, adopted from [179]

### 6.5.1 Development process

The manufacturing process chosen for the manufacture of the demonstrator panels is well defined, however, the size, thickness and curvature complexity of the panel presented a series of challenges which needed to be addressed. A development process was necessary prior to manufacture the final components. There are three main stages in this process; development of tooling, optimisation of thermal forming process and verification of 2D blackout frame printing mask.

#### 6.5.1.1 Design and manufacture of thermoforming and cutting tools

Two separate tools needed to be built. The first is a forming tool which is used to ‘guide’ the thermal forming process. The second is a panel-support tool which is necessary to support the formed panel whilst being machined into the final shape.

The two key elements of the forming tool are the control edges (A) and surfaces (B) as illustrated in Figure 6.18. During the thermoforming cycle the temperature of the sheet is raised until it gradually softens and starts sagging until the required curvature is achieved and it is the control edges and surfaces together with the thermal profile which control the final shape of the glazing panel. A smooth, lint-free cloth which is lightly stretched over the tool also assists the forming process. It aids in supporting the panel at the point of maximum formability of the panel.

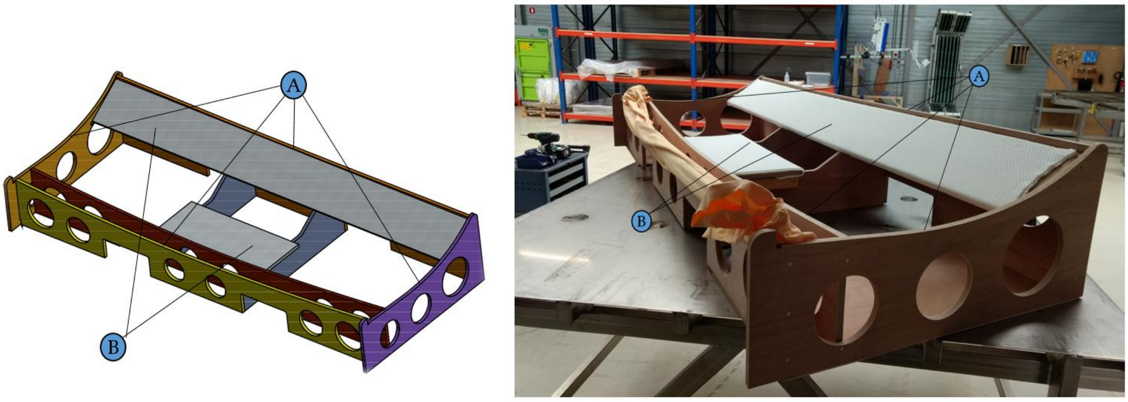


Figure 6.18: The thermoforming tool. The profile definition edges (A) define the curvature of the panel. Additional support surfaces (B) are added in order to add further control to the forming process.

Following the thermal forming process, the panel is cut into the final shape. The main purpose of the second tool is that of supporting the shaped panel whilst the machining process is carried out utilising an automated milling machine as illustrated in Figure 6.23.

### 6.5.1.2 Development of the panel thermoforming process

The process that was employed for the forming of the curved panel is a variation of drape forming. The PC sheet is placed onto a ‘female-form’ guide-tool and the sheet was allowed to deform under its own weight when heated to around 155°C. The shape and optical quality of the formed panel are significantly dependent on the exact temperature/time curing profile to which the panels are exposed during the forming cycle.

The tool with the flat sheet on top is placed within the oven and the thermal cycle is applied following which the curved glazing panel is obtained as illustrated in Figure 6.19.

Figure 6.19: The flat sheet of PC placed on the forming tool (left) and the curved panel following the curing cycle (right).

The thermal forming process parameters (rate of heating, hold at specific temperatures and rate of cooling) are of critical importance for the sheet to acquire the required shape whilst also retaining the optical qualities. As such, a series of forming cycles were necessary in order to optimise the parameters from an initial cycle set-up by an experienced engineer. In this case four thermal cycles were necessary until the required shaped panel was obtained.

### 6.5.1.3 Verification of the black-out print screen and cutting process

The final stage is the verification of the dimensions of the blackout mask print. The printing of the mask needs to be done on the flat sheets prior to forming. Verification and modification of the print-mask are necessary to ensure that the mask on the final formed panel has the correct dimensions. The print-mask is a key element of the component without which the panel could not be installed on in-service buses.

### 6.5.2 Demonstrator panels manufacture process

The production process of these glazing panels consists of the following main stages: Printing of the blackout mask, thermal forming process, coating of formed sheet, machining of the final shape, quality inspection and packaging.

#### 6.5.2.1 Blackout mask printing on 2D sheets

The first step of the production process is the printing of the blackout mask. There are two main purposes for the mask. The first one is a border blackout-print that serves to hide the adhesive joint and also protects the adhesive from UV exposure. Secondly, the parts needs to be marked with the required traceability and legislation marking as per R43 [164]. The printing process consists of a traditional silk-screen printing methodology utilising specialist paint that is compatible with PC. The flat sheets with the printed mask and marking are illustrated in Figure 6.20.

Figure 6.20: The flat sheets following the silk-screen printing process and detail of required markings.

#### 6.5.2.2 3D panel thermoforming

Following the mask printing process, the panels are placed onto the forming tool, placed within the oven and the thermal forming cycle (previously defined during the development phase) is applied. Set-up is illustrated in Figure 6.21.

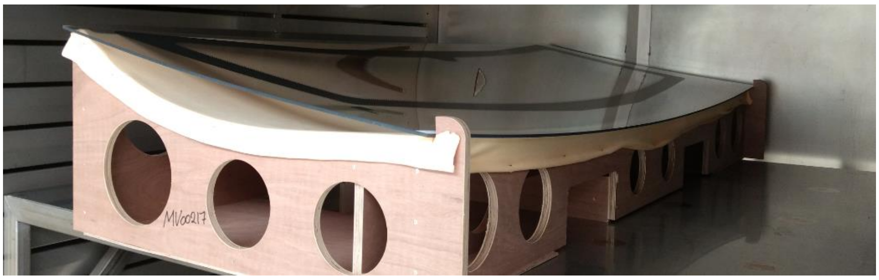


Figure 6.21: A PC flat sheet placed on the forming tool within the oven prior to the thermal forming stage.

### 6.5.2.3 Coating process

Following the forming cycle, the panels are transferred to the coating station. The coating was a silicone based 2-layer wet hardcoat, the AS4000 primer and hardcoat system manufactured by Momentive™ [181]. The coating process consists of the following main steps. Panels are hung onto an overhead conveyor system, thoroughly inspected and cleaned as necessary. The AS4000 primer is then applied by effectively washing down the panel with the primer as illustrated in Figure 6.22. The movement of the nozzle and the flow of primer are controlled in order to ensure a uniform coating (of approximately 2 μm) is applied to the whole panel. The application takes approximately three minutes following which a 20 minutes flash off period in necessary. The AS4000 top-coat is then applied in the same method. Following another flash off period the coated panel is heated to 130°C for 60 minutes to allow the wet-coating system to cure.

Figure 6.22: The application of the wet-coating system.

### 6.5.2.4 Machining of the final shape

The coating process is followed by a quality inspection stage. The number of visually visible defects are counted and the panels are quality graded. The panels with the required quality grading are then mounted on the cutting tool and machined into shape as illustrated in Figure 6.23.

Figure 6.23: The final manufacturing stage consists of machining the panel on a five-axis milling machine.

### 6.5.2.5 Finishing, quality control and packaging

The final process quality verifications are optical quality checks. An image consisting of a series of lines was projected through the glazing panel onto a measurement screen. The set-up and the two resultant projected images are illustrated in Figure 6.24. The degree of deviation and rotation of the projected images are measured. The effective focal length of the panel was measured to be 100 m, and the angular deviation was too low to be measured by this test set-up. This translates to optical distortions which are not detectable by the human eye when the glazing panel is in-service and illustrates the exceptional optical properties of the manufactured glazing panel.

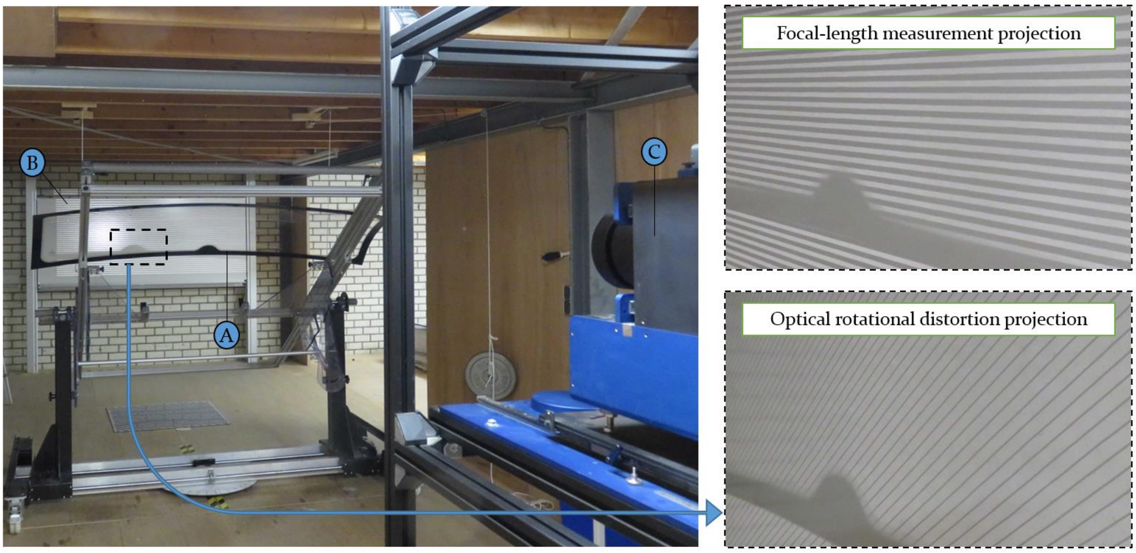


Figure 6.24: Set-up for optical quality inspection. A: Finished glazing panel, B: Projected image transmitted through the glazing panel, C: Projector.

### 6.5.2.6 Future implementation and developments

The final phase of this project, ongoing at the time of writing, consists of the installation of these finished panels (as illustrated in Figure 6.25) onto buses for in-service performance evaluation. The installation of six panels on buses operated by at least two operators was recommended by the author. This would help expose the panels to different environmental conditions and washing equipment and further build the confidence of the proposed technology. The panels should be inspected at regular intervals in order to ensure the integrity of the adhesive bond and monitor the scratch resistance performance of the hardcoat.

Figure 6.25: The finished PC glazing panel – ready for installation onto buses for in-service trials.

## 6.5.3 Cost analysis

A cost model of the PC demonstrator was developed. This cost analysis was carried out to evaluate if this technology could deliver cost effective lightweighting as well as highlight how design choices and production volumes affect the cost.

### 6.5.3.1 Development process cost

The development costs relate to the design and fabrication of the tooling jigs and the labour and materials consumed whilst determining the thermal forming process and verifying the other tools and processes as detailed in section 6.5.1. The total net development cost in this case study was £8,500.

- **Cost of manufacturing tooling**: The cost of the tools depend on the size and complexity of the glazing panel and the forecast production volumes. Wooden tools such as the ones used in this programme are acceptable for low volume production (typically below 100 per year). For higher volumes, a more durable tool would be constructed (additional costs are amortised by higher production volumes). The printing tool and the cutting tool costs would not change significantly for different shapes and/or production volumes.
- **Development process and material costs**: These are related to the complexity of the panel being produced and generally a simpler 2D curved panel would require less material and development time in order to define the production parameters.

### 6.5.3.2 Production run costs

The cost for extruded clear PC sheets (3 mm to 15 mm thickness) varies quite significantly (up to 200%) depending on the required optical quality. The price (2018) for the used Sabic Lexan ULG1003 PC which is Sabic highest quality extruded sheet PC, is £8.00 /kg.

The quantity of raw material utilised depends on the nesting of the glazing panel's flattened 2D pattern upon the extruded flat sheets. The extrusion process dictates the width of the sheets. The typical width within the EU for PC sheets of high optical quality is 2.05 m. The length of the sheets could be set according to request, up to practical handling limits. The nesting of the 2D print for this project is illustrated in Figure 6.26.

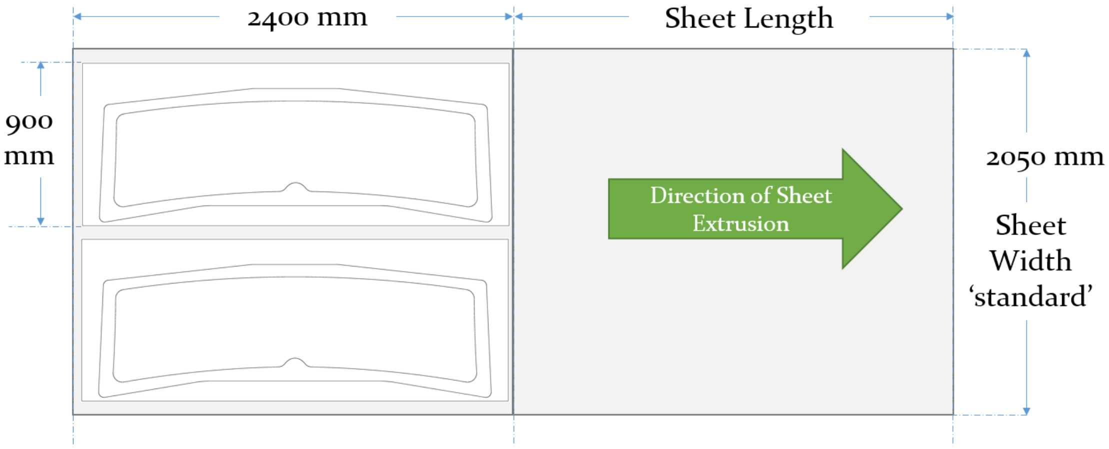


Figure 6.26: The material costs are highly dependent of the degree of utilisation of the flat sheet.

The particular size of the panel under consideration and its 3D curved profiles resulted in a material utilisation of 52% which equates to almost doubling the raw material cost.

A net cost estimation for the demonstrator panel, assuming an annual production of 500 units, is approximately £250. The lightweighting potential of this panel is approximately 13 kg. As per lifetime benefit estimates presented in section 2.4.3, this could yield a lifetime economic benefit through a reduction of fuel consumption of approximately £170.

ADL indicated that the cost of the currently utilised laminated glass panel is £155. This cost does not include tooling and/or development costs. A cost increase per bus of approximately £95 (£250 - £170) would be needed to implement the developed lightweight PC panel which is approximately 55% of the expected lifetime benefit. Hence, this lightweighting project would yield a net economic benefit to the bus operator even if the full cost increase is passed onto the bus operator.

## 6.6 Conclusions

The primary scope of the various work packages summarised in this chapter was that of assessing the feasibility of implementing PC glazing solutions onto ADL's buses.

- A state-of-the-art review illustrated that despite significant technological advancement of coating systems, the scratch resistance of PC glazing systems is still one of the main technical challenges. It was shown that there is a gap in the knowledge with regards to the performance of PC glazing systems utilised within the bus industry. A package of work was carried out to investigate this aspect.
- A testing set-up was designed to enable exposure of prospective glazing test panels to bus-wash environment. A frame was designed and built to allow different PC glazing samples to be mounted within a bus-wash with the test-panels being continuously exposed to brush-abrasive action during the normal daily operation of the bus-wash. The testing programme was successfully carried out and a suitable commercially available coated PC glazing system was identified. Results showed that PC glazing panels coated with an advanced 2-layer wet coat system (AS4000 manufactured by Momentive™) had an optical haze reading similar to that of glass following bus-washing exposure equivalent to 12-year bus lifetime.
- Fire-behaviour testing as required by R118 was carried out on the proposed PC glazing system in collaboration with Sabic. Tests confirmed that the glazing system is compliant with both the melting behaviour and vertical burns test.
- Adhesion compatibility testing was carried out in collaboration with SIKA AG and successfully identified a compatible adhesion system to allow bonding of glazing panels onto bus exterior surfaces.
- A case study project was created to implement the above identified solutions and replace a complex-shaped glass glazing panel currently installed on the Enviro400 DD bus by a PC glazing panel. Funding was secured from four participating partner and eight full-scale demonstrator panels were successfully manufactured. The PC glazing panel achieved a 57% weight reduction over the glass glazing panel. The achieved lightweighting translates to a net lifetime economic benefit. At the time of writing, the PC glazing panels are being installed by ADL on buses for in-service trials.

# 7

# CONCLUSIONS

This chapter presents a reflective review of the research undertaken. It defines the strengths of the studies undertaken, the influence on the sponsor company and details opportunities for future work.

## 7.1 Overview and key results of the research

The aim of the research programme sponsored by Alexander Dennis Ltd (ADL) was to identify feasible lightweighting opportunities for double-decker buses. As defined by industry reports, ADL's current bus structures conform to what is considered to be the current state-of-the-art in lightweight bus architecture. However, ADL supported this research programme to identify any feasible lightweighting opportunities which the company had not previously considered and investigated. ADL strategically chose not to provide specific direction or constrain the research to a specific structure of the bus. This approach led to an initial period of feasibility studies leading to the successful identification of a high impact, innovative lightweighting opportunity. This was the end-result of four contextual work packages consisting of:

- **Literature review:** An extensive review of literature relating to the utilisation of lightweighting technology within the bus industry was carried out. As current research and development in lightweight technology in the bus sector is limited, the review was extended to analyse whether lightweighting technologies applied to other industries could be carried over.

- **Analysis of ADL buses:** A detailed review of ADL bus structures, materials and manufacturing techniques was carried out. This was complemented by visits to various ADL manufacturing and testing plants and bus operator depots.
- **Review of ongoing lightweighting projects within ADL:** During the initial phases of this research, the author assisted in an extensive lightweighting opportunities identification exercise. This resulted in the implementation of various lightweighting projects yielding a 400 kg weight reduction of the Enviro400 DD.
- **Initial feasibility studies on identified lightweighting opportunities:** The work packages above yielded a filtered list of potential lightweighting opportunities. Initial feasibility studies where carried out, whilst seeking collaboration with industrial partners identified by the author, on components such as the fuel tank, handrails, glazing systems, chassis structure and upper-deck roof structure.

Review meetings with ADL concluded that a proposed novel lightweight upper-deck structure offered the potential of significant and high-impact lightweighting. The proposed lightweighting of the highest structure of a DD bus would result in lowering the bus centre of gravity which in turn would enable further lightweighting of lower structures to be implemented. Therefore, this proposal was chosen and a detailed design process of the proposed structure was carried out. This was necessary in order to ensure that the structure would be compliant with any relevant legislation, in particular the interior cabin volume requirements. The design illustrated legislation compliance and confirmed that necessary systems such as A/C ducting and lighting could be integrated within the design. Conservative weight estimates of the primary structural components demonstrated a 42% weight reduction equivalent to 260 kg could be achieved. The proposed system retains certain elements in the current structure including the roof sandwich panel. However, two of the key structural components necessitate the utilisation of materials and manufacturing methods which are novel to ADL and, to a great extent, the bus industry in general. These components are the structural curved beams and the curved glazing panels. Two separate work packages were organised to address these two components and assess the feasibility of the initial proposed solutions:

- **Braided FR curved structural beams**: A manufacturing method that could be feasibly utilised (considering cost and volume constraints of the bus industry) for the manufacture of braided FR thermoplastic-polymer composites was successfully identified. Demonstrator beam sections were successfully manufactured using the proposed method of bladder-assisted consolidation of braided commingled thermoplastic preforms. A finite-element methodology that would enable the design of these composite beam structures was proposed and verified though correlation of simulation performance data with data collected from three point bend tests carried out on prototype beam structures. Design guidelines including considerations of manufacturing volumes and costs were prepared for use by ADL.

- **Polymer glazing**: Investigations on the feasibility of polycarbonate glazing application within the bus industry identified that the abrasion resistance of PC glazing panels exposed to daily bus-washing was a key barrier to introduction of this technology. Hence, a novel testing set-up was designed to assess the performance of various commercially available coated PC glazing exposed to these conditions. Accelerated lifetime equivalent abrasion exposure testing was successfully carried out leading to the identification of a suitable coating system. Besides adequate abrasion resistance performance, fire resistance testing and bonding adhesive compatibility were established. The successful outcome of these testing programmes led to a full-scale demonstrator manufacture programme. A one-to-one replacement PC glazing panel was successfully manufactured achieving 57% component weight reduction when compared to the current laminated-glass glazing panel.

## 7.2 Key findings of the research

The following section summarises the key outcomes of this research relating to the design proposal of the upper-deck structure, assessment of braided beam suitability and PC glazing application readiness.

### 7.2.1 Lightweight upper-deck structure

- A novel lightweight, panoramic upper-deck structure concept was conceived, developed and proposed to ADL. The current rectangular roof shape was converted into a geometrically and aerodynamically efficient dome-type structure based on curved braided beam structures and lightweight polycarbonate glazing panels
- Weight calculations of the proposed structure, obtained from the detailed CAD model, indicate that a significant lightweighting potential of 42% (260 kg), relative to the current structure, is achievable.

- The weight reduction of the upper-deck structure results in a lower centre of gravity hence enabling lightweighting of other primary structures whilst still being compliant with legislative bus tilt-test requirements (260 kg weight reduction of the upper-deck structure would enable 1,820 kg lightweighting of the chassis structure)
- The project has a relatively low technical risk and low capital investment requirements enabling the possibility of a phased introduction to market.

### 7.2.2 Utilisation of FR braided beam structures within the industry

- A feasible low-cost composite manufacturing technique applicable for the low-volume production of curved beam structures was successfully identified. The methodology consists of consolidating braided preforms of hybrid commingled yarns in a simple passively-heated metal tool.
- The proposed manufacturing process was successfully demonstrated through the manufacture of demonstrator beam sections. A three-point bend testing jig was designed, constructed and the flexural stiffness of the beams measured.
- A macro FE design methodology that could be effectively used to design these beams structures was identified. The proposed methodology was verified by correlating the simulated performance of the test beams with physical test data achieved from the three-point bending tests.
- A cost analysis of different manufacturing volume scenarios was carried out. A key benefit of the proposed solution is the possibility of manufacturing demonstrator components at a relatively low capital investment. Once the viability of the proposed structure is verified and confirmed, further investment in advanced high-rate tooling could be made whilst still retaining the same material system previously developed during the demonstrator production stage.

### 7.2.3 Utilisation of polycarbonate glazing within the industry

- Following a feasibility study on the possibility of utilising PC glazing on buses, carried out in collaboration with Sabic BV, it was determined that there is a lack of knowledge on the abrasion resistance of coated PC glazing exposed to bus industry conditions. An innovative testing apparatus which enabled exposure of prospective glazing test panels to bus-wash environment was designed and implemented. Meaningful, repeatable, robust and real-world testing was successfully carried out and a suitable commercially available coated PC glazing system was identified. Results showed that PC glazing panels coated with an advanced 2-layer wet coat system (AS4000 manufactured by Momentive™) had an optical haze reading similar to that of glass following bus-washing exposure equivalent to 12-year bus lifetime.

- Fire-performance testing as required by R118 was carried out on the proposed PC glazing system in collaboration with Sabic. Tests confirmed that the glazing system is compliant with both the melting behaviour and vertical burn test.
- Adhesion compatibility testing was carried out in collaboration with SIKA AG and successfully identified a compatible adhesion system to allow bonding of glazing panels onto bus exterior surfaces.
- A case study project was created to implement the above identified solutions and replace a complex-shaped glass glazing panel currently installed on the Enviro400 DD bus by a PC glazing panel. Funding was secured from four participating partners and eight full-scale demonstrator panels were successfully manufactured. At the time of writing (Sept 2018), the PC glazing panels are being installed by ADL on buses for in-service trials. The PC glazing panel achieved a 57% weight reduction over the glass glazing panel and overall lifetime cost saving.

## 7.3 Impact on the industrial sponsor

The primary goal of the research and ADL's motivation for funding this project was that of identifying feasible lightweighting opportunities which were novel to ADL. The proposed upper-deck structure is a relatively low-investment, low-risk yet high impact project that would deliver a weight reduction equivalent to four passenger capacity. The project would also enable ADL to implement additional lightweighting projects returning a significant step-change reduction of the bus weight. The research carried out on key structural elements of the proposed structure could also be carried over to other bus structures. In addition to the identification of the lightweighting opportunity detailed in section 7.2, this research delivered various additional outcome for ADL:

- A technical guidelines report detailing the design and manufacture of braided FR composite beam structures. These structures are novel to ADL and the proposed methodology would enable ADL design engineers to evaluate the feasibility of utilising these beams and integrate them in other structures.

- A technical guidelines report on the design and manufacture of PC glazing. Similar to the report on the braided FR beam structures, this report details important aspects of the design, manufacture and cost in order to enable designer engineers to evaluate the utilisation of PC glazing in future applications.
- The PC glazing demonstrator panels installed on in-service buses will allow ADL to gain further knowledge of in-service performance of PC glazing panels. This would increase the confidence of ADL in this glazing option, the perception of which was negative before being presented with the results of these studies.
- The lightweight handrails feasibility study, partly carried out with Global Green Composites Ltd., led to the commencement of a commercial relationship with ADL supplying GRP moulded parts.
- A presentation was made by the author presenting the advantages of the ADL double-decker bus and ongoing novel research at the *International Automotive Glazing Conference* 2018, USA and the *Automotive Glazing Summit* 2019, Germany.
- Following a presentation by the author to the US based PC glazing manufacturer, Five Star Fabrication Inc., a tendering process for eventual supply of GRP panels was initiated.

## 7.4 Impact on the wider industry

One of the direct benefits of lightweighting is the increase of the bus industry's sustainability. The proposed upper-deck structure could enable an increased capacity of four passengers. Additionally, the proposed structures seek to enhance the passenger's experience and hence help to further increase uptake of public transport which is critical in increasing its economic sustainability and lower its environmental footprint.

Elements of the research carried out are also applicable to other mass-transit industries. Research carried out on braided FR beam structures and PC glazing has the potential to be applied to other industries, in particular the very light rail industry. One such project is the Coventry Very Light Rail Project where PC glazing could play an essential role in increasing passenger safety whilst enabling the vehicle (Figure 7.1) to achieve its target weight. It is foreseen that similar to the bus industry, future legislation would mandate the utilisation of impact-resistant safety glazing, where PC glazing would offer a significant lightweighting advantage (≈ 50%) over laminated glass [123]. The current project delivery team for the Coventry Very Light Rail Vehicle have actively consulted the author over the applicability of PC for the vehicle. Outcomes of this research programme and experience gained through the PC demonstrator manufacture work package are having a direct influence on the design process of these light rail vehicles.

Figure 7.1: Illustration of the proposed Coventry Very Light Rail System, reproduced from [182].

Additionally, implementation by ADL of the novel lightweighting technologies investigated throughout this research could enable further utilisation by other bus manufacturers and even other industries. The UK's Advanced Propulsion Centre (APC) release a number of technology roadmaps which are developed by consensus amongst a wide range of industry and academic experts. These roadmaps map out key technological developments the automotive industry will need to invest in the future to ensure continued success. Highlighted on the last version of the *Lightweighting vehicles roadmap,* illustrated in Figure 7.2, are the various technologies that were investigated throughout this EngD programme further illustrating the relevance and novel nature to industry of this research.

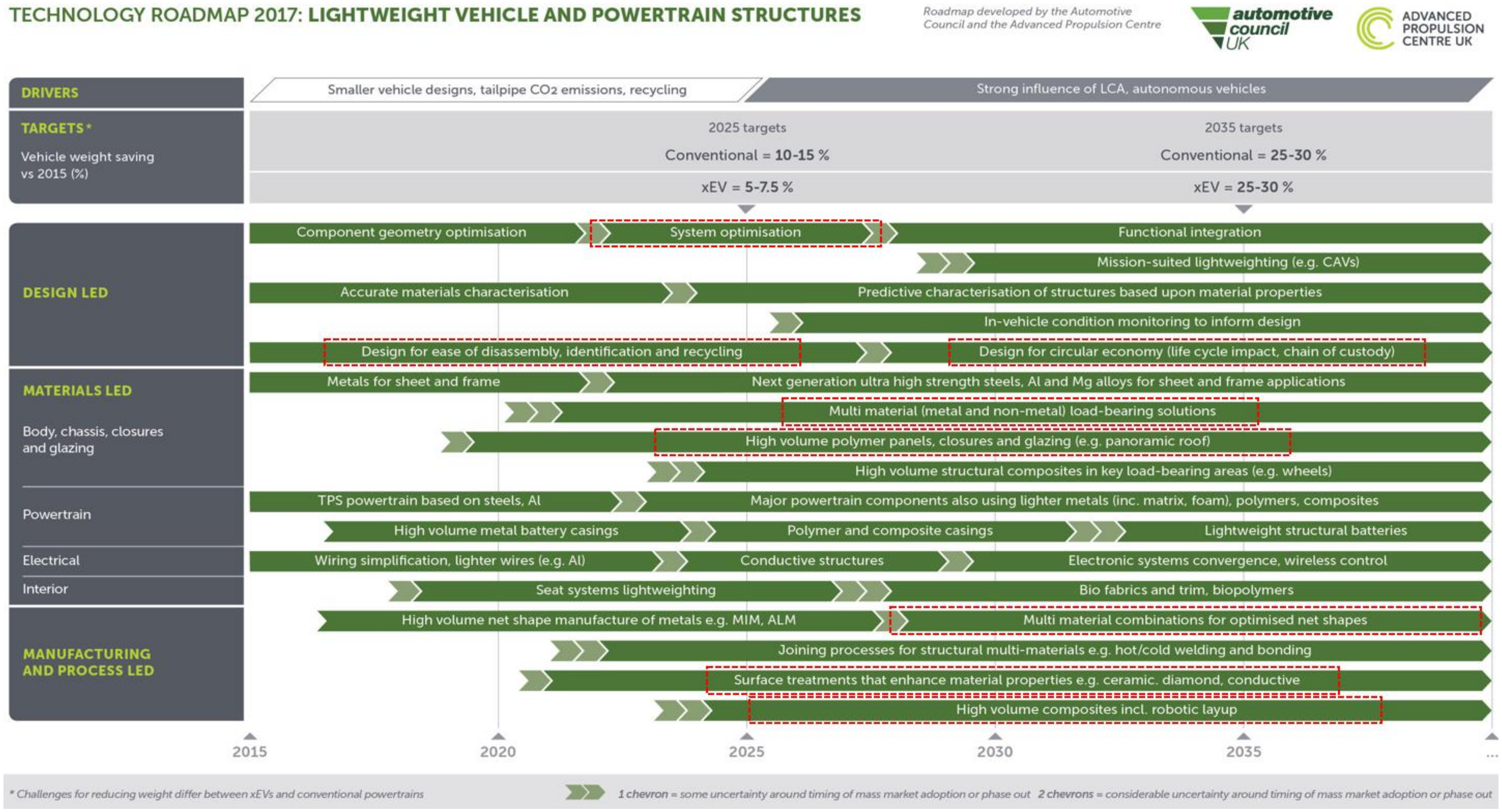


Figure 7.2: The APC 2017 *'Lightweight vehicle and powertrain structure'* roadmap. Technologies explored during this EngD research are highlighted in red, adopted from [183].

## 7.5 Recommendations for further research

The final section of this report summarises the various limitations of the work packages that were carried out and suggests future research in order to move further towards successful implementation of the proposed upper-deck onto ADL's buses as illustrated in Figure 7.3.

- **Polycarbonate glazing:** The installed demonstrator glazing panels should be monitored at frequent intervals (once every three months) to ensure that the forecasted scratch-resistance behaviour is achieved. Frequent monitoring is necessary as the early detection of failures would help in the determination of the root cause of the failure. Additionally, the author recommends that the PC glazing demonstrator development programme is repeated on another glass glazing panel (front-facing panel of the upper-deck of an Enviro400). This glazing panel is a front-facing glazing panel installed at a different location than the one considered during this research and would allow a much more complete set of in-field performance data to be collected. The weight reduction possible through this glazing panel replacement is expected to be approximately 25 kg.
- **Braided FR composite beam structures:** The introduction of braided FR beams onto a bus would enable further verification of the developed design and manufacturing methodology. The ideal structure for the introduction of this technology would be the handrails. Handrails would provide a low-cost and low-risk scenario for the introduction of this technology allowing ADL to gain further knowledge and confidence in this novel technology as well as start setting-up a supply chain which in the case of composite structures is still far from being mature.

Following the proposal of the upper-deck structure, three significant risks were identified (design legislation and packaging requirements, PC glazing performance and braided beam structure manufacture and cost). The successful outcomes of the three work packages that were carried addressing these risks should now warrant further investment in the concept by ADL. The manufacturability of the major structural components of the structure have been confirmed by the various work packages carried out throughout this EngD research, and hence the next stage of this project should consist of further detailed design focussed on the following aspects:

- **Design optimisation:** Optimisation of the proposed upper-deck structure could yield further lightweighting potential. The study should seek to identify the optimum number of supporting vertical beams which would hence influence the size (and thickness) of the required glazing panels.

- **Joining of the braided beam structured to the waist-rail and cantrail beams:** The curved braided FR beam structures would need to be joined to the waist-rail beam and the roof cantrail beams. The thermoplastic braided FR beam structures could allow the integration of novel joining fixtures that would enable effective load transfer and possibly an improvement of the current assembly method.

- **Detailed analysis of bonding/assembly of glazing panel:** The current design proposes that the curved PC glazing panel are bonded onto the curved beams. Initial feasibility studies indicated that the proposed adhesive is capable of tolerating the movement of the glazing panels caused by thermal expansion. Further investigation would be necessary to determine the extent of panel movement the adhesive could tolerate which could limit the size of the glazing panels.

- **Emergency exits:** Detailed design of the provision for emergency exits is required. Initial feasibility studies have illustrated that this could be achieved in various ways such as having mechanically releasable frames for the glazing panels assigned as emergency exits, or having the emergency exit glazing panels made out of toughened glass.

- **Cabin environment conditioning:** The increased glazing area of this panoramic upper-deck structure would expose the upper-deck cabin to an increased degree of solar heat gain which could have a significant impact on passenger comfort and A/C power requirements. Possibilities of mitigating this have been identified, however further detailed analysis and simulation is necessary.

- **Structural performance in roll-over crash scenario:** Even though legislation does not require DD buses to comply with R66 roll-over requirements, ADL buses are conformant. The performance of the proposed structure as opposed to the current structure in a roll-over scenario should also be simulated.

- **Cost analysis:** A detailed cost analysis comparing the proposed structure with the current should be carried out. The detailed design work noted above is necessary to ensure that the cost estimate is realistic.

Figure 7.3: A graphical representation of the Enviro500 equipped with the lightweight upper-deck structure.

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