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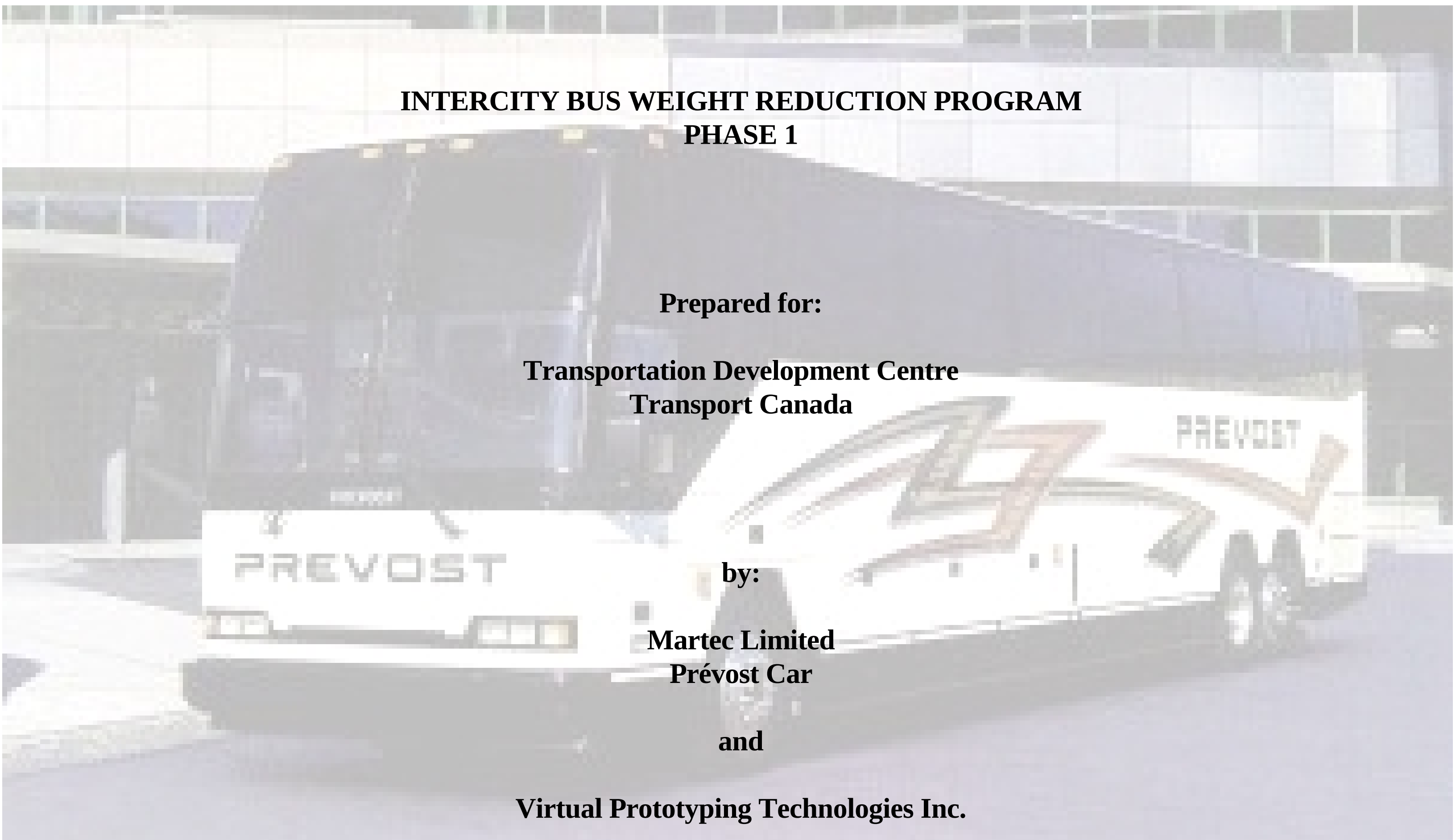

INTERCITY BUS WEIGHT REDUCTION PROGRAM
PHASE 1

Prepared for:

Transportation Development Centre
Transport Canada

by:

Martec Limited
Prévost Car

and

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January 2000

TP 13560E

INTERCITY BUS WEIGHT REDUCTION PROGRAM – PHASE I

by:

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January 2000

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Un sommaire français se trouve avant la table des matières.

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16. Abstract

This study investigates possible design concepts to reduce the weight of intercity buses. The regulatory and operational problems associated with heavy intercity buses were defined and the parameters important in defining the main thrust behind the production of lighter intercity buses were identified.

A typical intercity bus was selected and the components with potential for weight reduction were identified. From these, a number of structural components were selected for weight reduction.

The evaluation was performed through the development of lightweight design concepts for each component, and analyses of bus numerical finite element (FE) models. The life cycle costs (LCCs) of each design concept were determined and, based upon the LCC and other important considerations, the most promising design concepts were chosen for future consideration in the development of lighter intercity buses.

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16. Résumé

La présente étude a consisté à élaborer des concepts techniques permettant d'alléger les autocars. Les chercheurs ont d'abord cerné les problèmes réglementaires et opérationnels associés à la lourdeur des autocars, puis ont défini les grands paramètres de l'objectif global sous-jacent à la production d'autocars allégés.

Un autocar type a été sélectionné et on en a repéré les composantes susceptibles d'être allégées. Parmi celles-ci, un certain nombre d'éléments de structure ont été retenus.

L'évaluation a comporté l'élaboration de concepts techniques pour chacun de ces éléments et des analyses de modèles numériques aux éléments finis de l'autocar. Le coût du cycle de vie (CCV) associé à chaque concept technique a été déterminé. Divers facteurs, dont le CCV, ont ensuite servi à établir la liste des concepts les plus prometteurs pour la construction d'autocars allégés.

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EXECUTIVE SUMMARY

This report presents the results of a study into the development of design concepts for lighter intercity buses. The work was performed for the Transportation Development Centre by Martec Limited, with guidance in the area of the bus manufacturing industry provided by Prévost Car.

The progression of weight increase of intercity buses for one company is shown in Figure 1, where the weights are presented over the past 25 years for buses manufactured by Prévost Car. As shown in this plot, the weight of intercity buses increased by 20 percent from 1974 until the mid 1990s where the introduction of the 13.7 meter (45 ft.) buses further exacerbated the problem. However, recent weight reduction initiatives taken by Prévost Car have resulted in a "levelling off" in the bus weight.

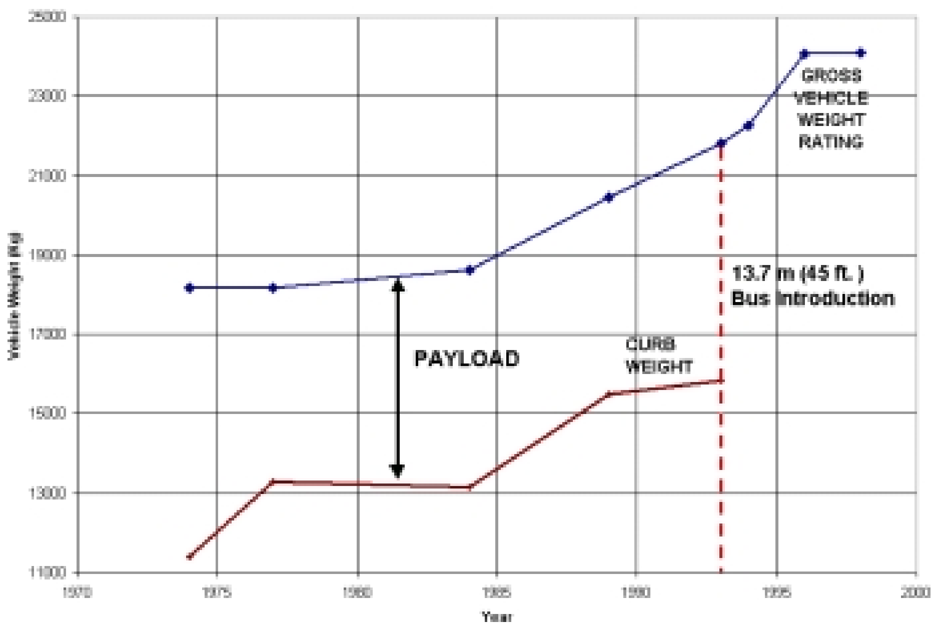

Figure 1: Historical Development of Prévost Cars' Intercity Bus Weight

Until recently, the weight of intercity buses was not an issue with regulatory agencies, operators, and/or manufacturers. In 1988, a memorandum of understanding (MOU) was developed under the auspices of the Transportation Association of Canada to bring about greater uniformity in provincial regulations regarding vehicle size and weight. Under the MOU, the weight limits of the front, drive, and tag axles were set at 5,550 kg, 9,100 kg, and 6,000 kg, respectively. Surveys revealed that out of a total of 140 observations, 50 percent of the buses had steering axle weights exceeding 5,500 kg.

In 1997 the front axle capacity was increased to 7,250 kg. Recent surveys indicate that out of 200 observations, 3 percent of buses had the steering axle over the new regulated limit and 18 percent had a weight on their drive axle exceeding the 9,100 kg limit. Therefore, the weight problem had been regularly identified as exceeding regulatory limits.

During the same period of time, bus manufacturers were coming under increased financial pressure through competition to reduce bus life cycle costs (LCCs) while maintaining safety, comfort, and a bus life of about 3,200,000 km (2,000,000 mi) or 15 years. Manufacturers were searching for strategies for reducing bus weight that would also result in LCC reduction. The estimated LCC of intercity buses is presented in the table below. LCC such as operator/driver expenses, permits, taxes, insurance, licensing, financing, etc. are not considered in this study. These costs are not affected by weight reduction.

Table 1: Estimated Intercity Bus Life Cycle Cost

Life Cycle Cost Component	**Individual Intercity Bus Cost (15 years) $K**	**Intercity Bus Fleet Cost (1 year) $M**	**Intercity Bus Fleet Cost (15 years) $M**
Operator:			
Fuel	262.5	70.0	1,050.0
Maintenance	262.5	70.0	1,050.0
Societal:			
Road Infrastructure	84.4	22.5	337.5
Pollutant Emissions	151.9	40.5	607.5
Fabrication	300.0	1,200.0	1,200.0
Total	**$1,061.3**	**$1,403.0**	**$4,245.0**

In addition, there was a growing concern regarding emissions produced by the transportation industry. Based on the total annual mileage of approximately 375 million km, the total fuel used by intercity buses per year is estimated at 110.5 million L. While intercity buses comprise a small part of the overall greenhouse gas (GHG) problem, heavier buses produce more emissions. Canada’s commitment to the 1997 Kyoto protocol is to reduce GHG emissions by 6 percent below the 1990 levels, from 2008 and 2012. Reducing intercity bus weight is one approach that can address this problem.

In this project, Martec Limited worked very closely with Prévost to identify potential means of reducing the weight of Prévost intercity buses. This work is Phase 1 of a three-phase project to develop conceptual designs for lightweight buses (Phase 1), manufacture and test prototypes of the concepts (Phase 2), and develop full-scale bus components for structural and in-service (road) testing (Phase 3).

The major structural components of the bus (roof, floor, and side truss) are identified as the areas to be studied for weight reduction concepts. These components were selected primarily because they comprise almost 20 percent of the total bus weight and any potential weight savings here would result in a significant overall reduction of the total bus weight.

The determination of lightweight design concepts for each of the selected bus structural components was performed through the analysis of a finite element (FE) model (see Figure 2) of a typical intercity bus. The model chosen for this work is the Prévost Car XLII intercity coach. The original/ current configuration of each component was determined and an FE analysis performed to define a baseline for the new concept development. New structural concepts were then developed for the

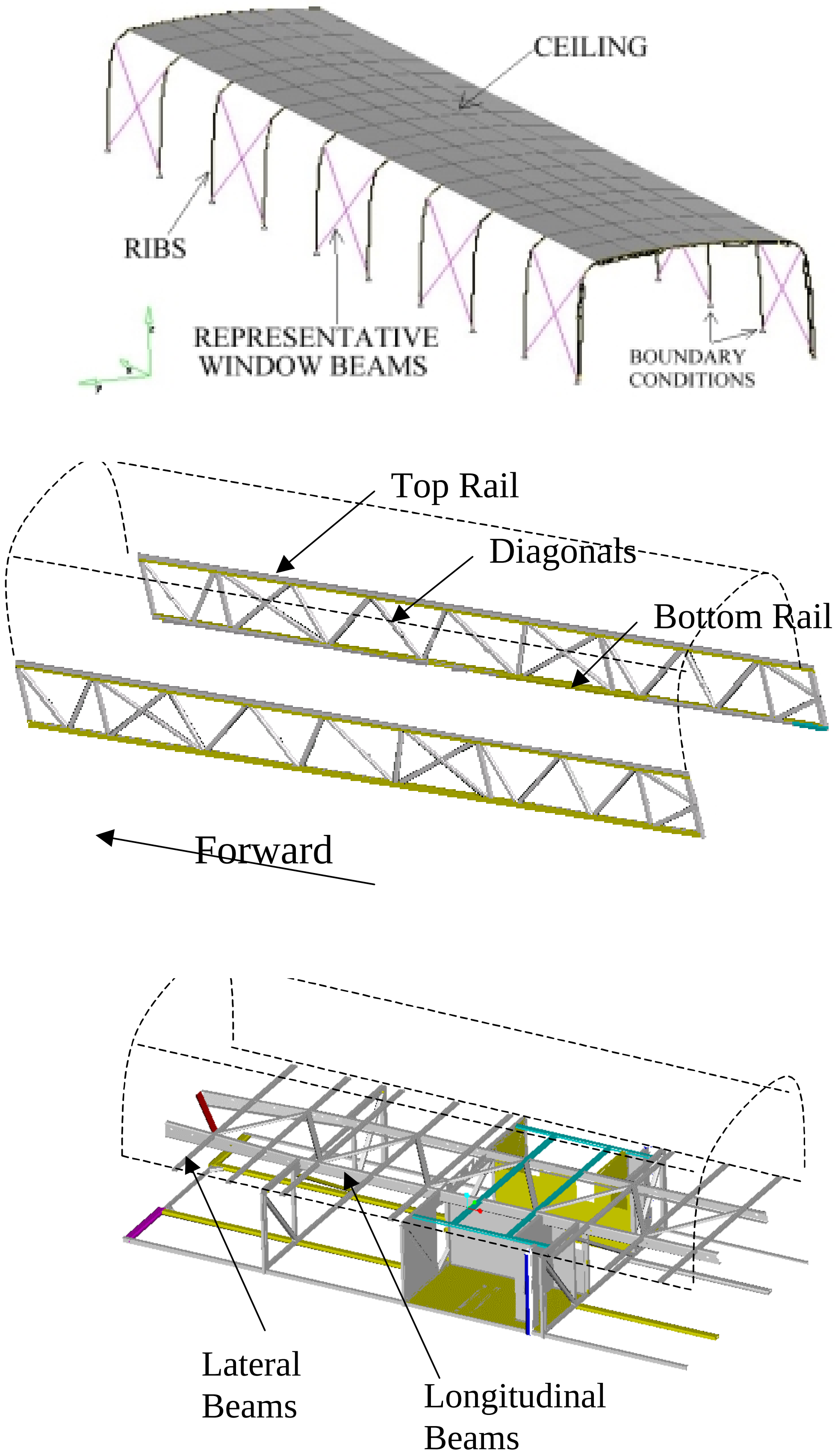

Figure 2: FE Models of the Intercity Bus Roof, Side Truss, and Floor

floor, roof, and side truss, using new configurations and/or materials. These concepts were incorporated into the FE model and optimized to provide a new component design that matches the stiffness and maintains the stress levels within the design criteria.

An analysis was also performed to determine whether gluing all of the window in place would significantly increase the bending moments of inertia of the bus. The results showed that an approximate 5 percent increase in stiffness (maximum) can be achieved by doing so. This is based upon the stiffness of the original structure and not for the new design concepts. It was found that fixing the windows in the model of the new roof, floor, and truss produces a negligible increase in stiffness.

An analysis was carried out to determine whether further weight reduction can be achieved by considering the combination of the stiffness of the three (roof, floor, and truss) components. Combining the bus structural components resulted in an increase in the moment of inertia. A reduction in stress resulted from an increase in moment of inertia. The stress reduction permits a reduction in the size of the top and bottom truss chord for additional weight saving.

The most likely design concepts (to produce lightweight buses) were chosen based upon the LCC savings of each new concept. A rating system (see Table 2) was developed, with the most promising concepts having the lowest rating. The determination of the rating was based upon weight reduction performance and resistance to corrosion, collision, and fatigue.

Table 2: Intercity Bus Optimal Lightweight Design Concepts

Optimal Floor Configuration Design Concept	**Weight (kg)**	**Weight Savings (kg)**	**Overall Rating**
Baseline – steel frame/plywood	740		100.0
Semi-supported structural floor 20 mm core steel sandwich panel	610	130	97.0
Unsupported Baultar structural floor	436	304	82.9
Unsupported structural floor 50 mm core steel sandwich panel	463	277	85.0
Unsupported structural floor 50 mm core Al sandwich panel	350	390	83.4

Optimal Side Truss Configuration Design Concept	**Weight (kg)**	**Weight Savings (kg)**	**Overall Rating**
Baseline – HSS steel	462.4		100.0
Diagonals replaced with steel sandwich panels	413.4	49.0	94.6
All aluminum truss	370.3	92.1	87.6
Aluminum rails with aluminum sandwich panels	285.3	177.1	73.8
Aluminum rails with composite panels	283.3	179.1	76.0
Steel rails with composite panels	375.4	87.0	88.4
Composite rails with composite panels	274.3	188.1	74.5

Optimal Roof Configuration Design Concept	**Weight (kg)**	**Weight Savings (kg)**	**Overall Rating**
Baseline –SS ribs/aluminum skin	584		100.0
Aluminum ribs/aluminum skin	290	294	68.5
Aluminum ribs with fibreglass sandwich panels	254	330	76.9
Aluminum ribs with aluminum sandwich panels	254	330	64.4

The most promising design concepts were based on sandwich panel construction using foam cores with either aluminum or fibreglass skins. All proposed concepts had ratings lower than the current configuration.

From the analysis of the lightweight concept designs of the roof, floor, and side truss, an estimate of the total possible weight savings was generated. This is summarized in Table 3 where the maximum weight saved of all of the concept designs is presented, indicating that a 50 percent weight savings is possible on the intercity bus structural components.

Table 3: Overall Intercity Bus Lightweight Design Concept Weight Savings

Component	Maximum Weight Savings	
	(kg)	(percentage)
Roof	330	57
Side truss	188	41
Floor	390	53
Average	N/A	50

These components comprise 17 percent of the total bus weight. Therefore, an overall intercity bus weight savings of approximately 9 percent is possible by optimizing the bus structure. Further optimization of the components is expected to produce even greater weight savings. It is estimated that full optimization will generate a weight savings of approximately 20 percent.

Assuming that current intercity buses have axle weights at the MOU limits, and based on the weight saved from the proposed structural concept designs, a 9 percent reduction in weight will reduce the front axle weight to 6,788 kg. Assuming an overall uniform 20 percent reduction in the bus weight, the axle weight would be reduced to 6,224 kg; these weights are well below the MOU limit, and provide a significant margin of safety (see Table 4).

The MOU rear (drive) and tag axle limits are 9,100 kg and 6,000 kg, respectively. As for the above prediction for the front axle, a 9 percent and 20 percent reduction in the weight of the bus would decrease the drive and tag axle weights to those as specified in the table.

Table 4: Potential Intercity Bus Axle Weight Reduction

Axle Location	Current Weight (kg)	Potential Weight Reduction			
		9 Percent		20 Percent	
		Wt saved (kg)	Weight (kg)	Wt saved (kg)	Weight (kg)
Front	7,250*	462	6,788	1,026	6,224
Drive	9,100*	579	8,521	1,287	7,813
Tag	6,000*	382	5,618	849	5,151

*Assumes the weight is the same as the MOU limit.

Assuming that the level of damage produced by intercity buses is 50 percent of that produced by urban buses, the estimated LCC cost savings (15 years) for a 9 percent and 20 percent weight reduction for road infrastructure damage are $2.1M and $4.5M, respectively.

Based upon the total annual mileage (approximately 375 million km) of intercity buses in Canada, the LCC savings (15 years) for a 9 percent and 20 percent weight reduction for pollutant emissions are $54.7M and $121.5M, respectively.

A 9 percent bus weight reduction would result in a reduction of approximately 17.7 million kg (17.7 Ktonne) of CO_2 per year. Over the life of the fleet (15 years), the total reduction in CO_2 would be 266 million kg (266 Ktonne). A 20 percent intercity bus weight reduction will reduce GHG emissions by 591 million kg (591 Ktonne) over the life of the fleet.

The individual LCC savings resulting from the reduced weight of an intercity bus by 9 percent is summarized in Table 5. This reflects the total intercity bus industry savings in Canada based on the present bus population. As shown, the overall cost savings associated with a 9 percent decrease in intercity bus weight over a 15-year period is estimated at $127.8M. If a 20 percent weight reduction could be achieved, the total LCC savings would be approximately $283.5M. It is predicted that fabrication costs can be maintained at the current levels.

Table 5: Intercity Bus Life Cycle Cost Variance due to a 9 Percent and 20 Percent Weight Reduction

Life Cycle Cost Component	**Cost Variance ($M)**	
	9 Percent Savings	20 Percent Savings
Operator:		
Fuel	-47.3	-105.0
Maintenance	-23.7	-52.5
Societal:		
Road infrastructure	-2.1	-4.5
Pollutant emissions	-54.7	-121.5
Fabrication	0.0	0.0
Total	**$-127.8M**	**$-283.5M**

The proposed plan for the follow-on Phase 2 project will involve the selection of the most promising design concepts for prototype manufacturing. These prototypes will be fabricated and tested to ensure that the concept designs are sound before full-scale development.

Significant weight savings are possible from the proposed design concepts. Detailed design and implementation of these designs into the intercity buses will result in appreciable LCC savings, axle(s) weight reduction, infrastructure damage reduction, and GHG emissions reduction.

SOMMAIRE

Le présent rapport rend compte des travaux d'élaboration de concepts techniques permettant d'alléger les autocars. Ces travaux ont été réalisés pour le compte du Centre de développement des transports par Martec Limited, avec les conseils de Prévost Car pour ce qui est des questions pratiques touchant la construction des autocars.

La figure 1 illustre la courbe d'augmentation du poids des autocars d'un constructeur, Prévost Car, au cours des 25 dernières années. Comme on peut le voir, le poids des autocars a augmenté de 20 p. cent de 1974 au milieu des années 1990, époque où l'apparition des autocars de 13,7 m (45 pi) a amplifié le problème. Mais les récentes initiatives prises par Prévost Car pour alléger ses véhicules ont infléchi la courbe.

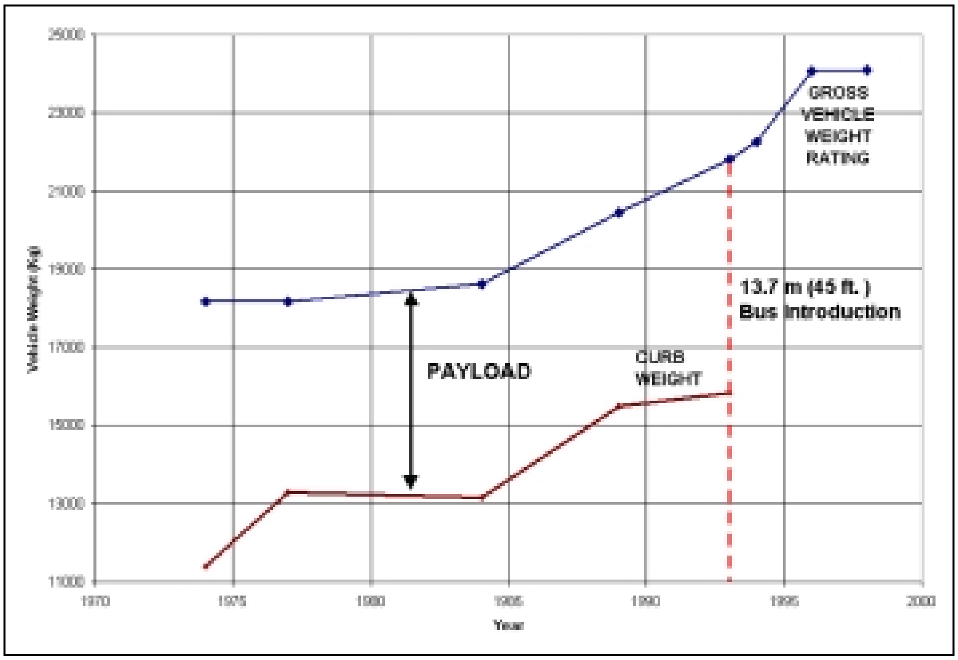

Figure 1 : Évolution historique du poids des autocars de Prévost Car

Jusqu'à récemment, les organismes de réglementation, les exploitants et/ou les constructeurs se souciaient peu du poids des autocars. En 1988, un protocole d'entente (PE), élaboré sous l'égide de l'Association des transports du Canada, visait à instaurer une plus grande uniformité des règlements provinciaux relatifs aux poids et dimensions des véhicules. En vertu de ce PE, les limites de poids de l'essieu avant, de l'essieu moteur et de l'essieu traîné ont été établies à 5 500 kg, 9 100 kg et 6 000 kg respectivement. Mais des études ont révélé que sur un total de 140 autocars, 50 p. cent dépassaient les 5 500 kg de limite de poids de l'essieu directeur.

En 1997, la limite de poids de l'essieu avant a été portée à 7 250 kg. Encore là, des études ont montré que sur 200 autocars, 3 p. cent dépassaient la nouvelle limite réglementaire touchant l'essieu avant, et 18 p. cent, la limite de 9 100 kg pour l'essieu moteur. Le dépassement des limites de poids a donc été reconnu comme un problème récurrent.

Pendant ce temps, les constructeurs d'autocars ont senti la nécessité, pour faire face à des pressions financières croissantes et à la concurrence, de réduire le coût du cycle de vie (CCV) de leurs véhicules, mais sans compromission aux chapitres de la sécurité, du confort et de la durée de vie des autocars, laquelle s'établit actuellement à environ 3 200 000 km (2 000 000 mi), ou 15 ans. D'où la recherche de stratégies pour réduire à la fois le poids et le CCV des autocars. Le tableau 1 ci-après présente le CCV estimatif d'un autocar. Les dépenses des exploitants/conducteurs, les coûts des permis, taxes, assurances et permis de conduire, les frais de financement, etc. ne sont pas pris en compte dans la présente étude : l'allégement de l'autocar n'a aucun effet sur ces coûts.

Tableau 1 : Coût estimatif du cycle de vie d'un autocar

Élément de coût du cycle de vie	**Coût pour un autocar (15 ans) millier $**	**Coût pour un parc d'autocars (1 an) millier $**	**Coût pour un parc d'autocars (15 ans) millier $**
Exploitant :			
Carburant	262,5	70,0	1 050,0
Entretien	262,5	70,0	1 050,0
Société :			
Infrastructure routière	84,4	22,5	337,5
Émissions polluantes	151,9	40,5	607,5
Fabrication	300,0	1 200,0	1 200,0
Total	**1 061,3 $**	**1 403,0 $**	**4 245,0 $**

Autre facteur en faveur de l'allégement : la pollution engendrée par le secteur des transports, qui soulève de plus en plus d'inquiétudes. On estime en effet que chaque année, les autocars consomment 110,5 millions de litres de carburant pour parcourir quelque 375 millions de kilomètres. Même si les autocars contribuent peu au problème global des gaz à effet de serre, plus ils sont lourds, plus ils produisent des émissions polluantes. En signant le Protocole de Kyoto en 1997, le Canada s'est engagé à réduire de 6 p. cent, par rapport aux niveaux de 1990, ses émissions de gaz à effet de serre, d'ici 2008 à 2012. L'allégement des autocars est un moyen de se rapprocher de cet objectif.

Dans le cadre du présent projet, Martec Limited a collaboré de très près avec Prévost Car afin de cerner des moyens d'alléger les autocars Prévost. Ces travaux constituaient la première phase du projet, qui visait l'élaboration de concepts techniques pour autobus allégés; deux autres phases sont prévues, qui viseront la fabrication et l'essai de prototypes représentant ces concepts (phase 2) et le développement de composantes en vraie grandeur pour des essais d'endurance (au banc) et des essais en service (sur route) (phase 3).

Les éléments de structure principaux (toit, plancher, structure treillis latérale) se sont révélés les meilleurs candidats à envisager pour l'allégement de l'autocar. La principale raison pour laquelle ces éléments ont été retenus est qu'ils représentent près de 20 p. cent du poids total de l'autocar : tout allégement de ces éléments entraînera forcément une réduction notable du poids total de l'autocar.

Les concepts techniques correspondant aux versions «allégées» de chacun des éléments de structure retenus ont été élaborés à la faveur d'analyses d'un modèle aux éléments finis d'un autocar type (voir la figure 2). Le véhicule retenu pour ces travaux est le XLII de Prévost Car. La configuration originale/actuelle de chaque élément a été déterminée et une analyse par éléments

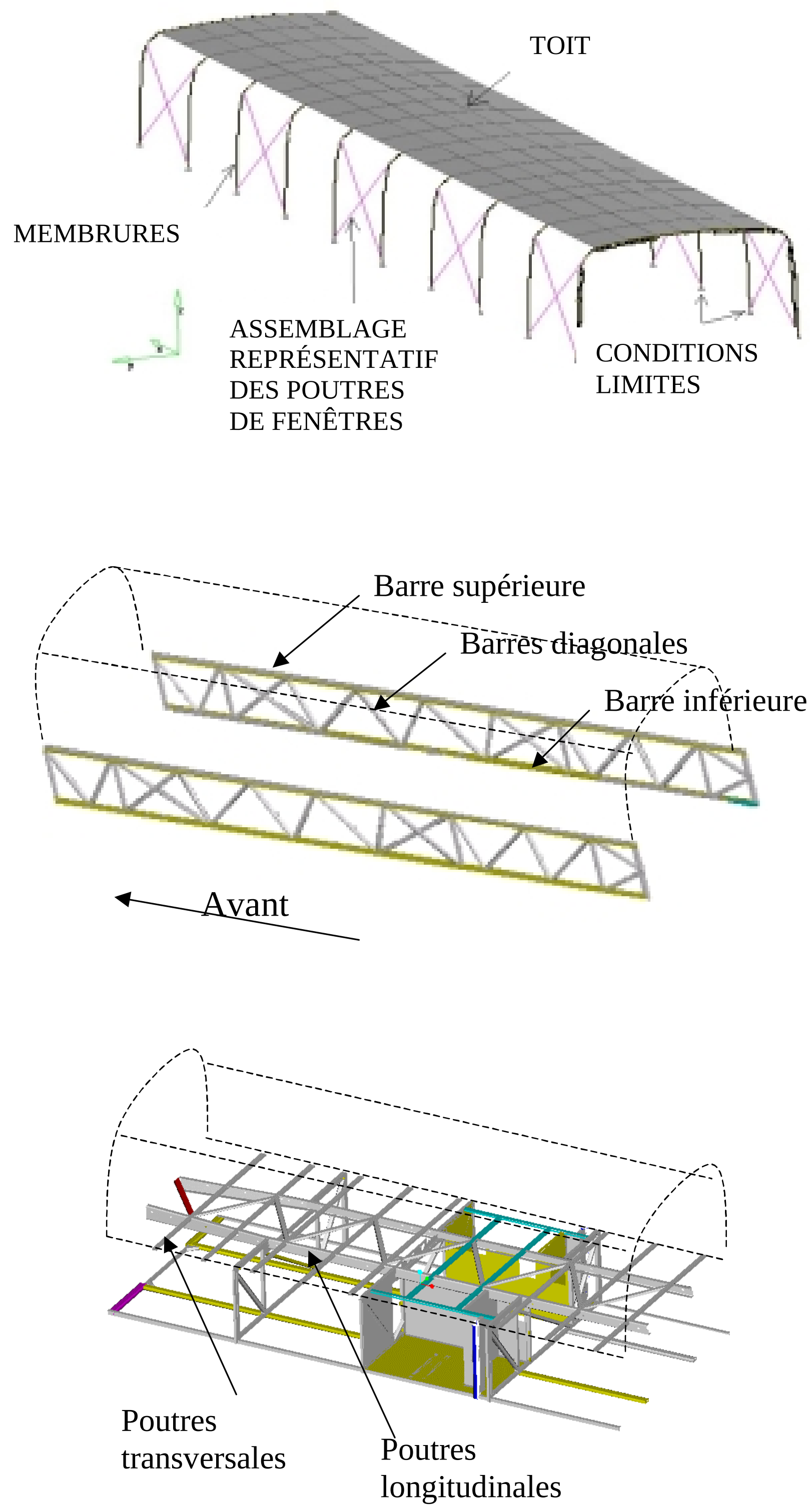

Figure 2 : Modèles aux éléments finis du toit, de la structure treillis latérale et du plancher

finis a été réalisée afin d'établir une base de référence pour l'élaboration de nouveaux concepts techniques. Des concepts faisant appel à des configurations et/ou matériaux nouveaux ont été élaborés pour le plancher, le toit, la structure treillis latérale, et ont été incorporés au modèle aux éléments finis et optimisés. Il en est résulté des concepts techniques qui respectent les critères de calcul en ce qui a trait à la rigidité et au niveau d'efforts.

Une analyse a également été effectuée pour déterminer si le fait de coller toutes les fenêtres en place augmenterait de façon significative le moment d'inertie de flexion de l'autocar. Les résultats ont révélé qu'une telle mesure entraînerait une augmentation (maximale) d'environ 5 p. cent de la rigidité de la structure actuelle (et non de la structure répondant aux nouveaux concepts). Ainsi a-t-il été déterminé que le collage des fenêtres aurait un effet négligeable sur la rigidité d'une structure comportant des concepts techniques de toit, de plancher et de structure treillis latérale améliorés.

Les chercheurs ont effectué une analyse pour déterminer si en combinant la rigidité des trois éléments de structure (toit, plancher, structure treillis latérale) on pourrait encore alléger l'autocar. Une telle combinaison entraîne une augmentation du moment d'inertie, qui entraîne à son tour une diminution des efforts. Or, la diminution des efforts permet de réduire les dimensions des barres supérieure et inférieure de la structure treillis latérale, ce qui se traduit par une autre réduction de poids.

Les concepts techniques les plus prometteurs pour ce qui est de l'allégement des autocars et de la diminution du CCV ont été retenus. Un système de cotation (voir le tableau 2) a été élaboré, les cotes les plus basses correspondant aux meilleurs concepts. Ces cotes ont été attribuées d'après la performance du concept aux chapitres de l'allégement et de la résistance à la corrosion, aux collisions et à la fatigue.

Les concepts techniques les plus prometteurs utilisent des panneaux sandwich à âme de mousse et revêtement d'aluminium ou de fibre de verre. Tous les concepts proposés ont obtenu des cotes inférieures à celle de la configuration actuelle.

L'analyse des concepts de toit, de plancher et de structure treillis latérale allégés a ensuite permis d'évaluer l'allégement global potentiel. Ces données sont résumées au tableau 3, où chacun des concepts menant à la réduction maximale de poids a été retenu. On voit donc qu'il est possible de réduire de 50 p. cent le poids des éléments de structure étudiés.

Ces éléments de structure comptent pour 17 p. cent de tout le poids de l'autocar. Il est donc possible de réduire d'environ 9 p. cent le poids de l'autocar en optimisant seulement ces éléments. Une optimisation plus poussée des éléments devrait même mener à un allégement encore plus marqué. On estime qu'une optimisation maximale mènerait à un allégement d'environ 20 p. cent.

En supposant que le poids des essieux des autocars actuels est à la limite du poids permis par le PE, l'allégement promis par l'application des concepts techniques proposés entraînerait un allégement de 9 p. cent de l'essieu avant, qui ne pèserait plus que 6 788 kg. En supposant également un allégement global de l'autocar de 20 p. cent, le poids des essieux ne s'élèverait qu'à 6 224 kg, soit beaucoup moins que la limite permise par le PE. On obtiendrait en outre une bonne marge de sécurité (voir le tableau 4).

Les limites de poids établies par le PE pour l'essieu arrière (moteur) et l'essieu traîné sont de 9 100 kg et 6 000 kg, respectivement. Comme la prédiction concernant l'essieu avant vaut aussi pour l'essieu arrière, un allégement de 9 p. cent et de 20 p. cent de l'autocar entraînerait une diminution du poids de l'essieu arrière et de celui de l'essieu traîné, les portant aux valeurs indiquées dans le tableau.

Tableau 2 : Concepts techniques optimaux pour l'allégement des autocars

Concept technique optimal pour le plancher	**Poids (kg)**	**Réduction du poids (kg)**	**Cote globale**
Base de référence – châssis métallique/contreplaqué	740		100,0
Panneau sandwich à âme d'acier de 20 mm pour plancher porteur semi-renforcé	610	130	97,0
Plancher porteur Baultar non renforcé	436	304	82,9
Panneau sandwich à âme d'acier de 50 mm pour plancher porteur non renforcé	463	277	85,0
Panneau sandwich à âme d'aluminium de 50 mm pour plancher porteur semi-renforcé	350	390	83,4

Concept technique optimal pour la structure treillis latérale	**Poids (kg)**	**Réduction du poids (kg)**	**Cote globale**
Base de référence – profilés creux en acier	462,4		100,0
Barres diagonales remplacées par des panneaux sandwich acier	413,4	49,0	94,6
Treillis tout aluminium	370,3	92,1	87,6
Barres aluminium avec panneaux sandwich aluminium	285,3	177,1	73,8
Barres aluminium avec panneaux composite	283,3	179,1	76,0
Barres acier avec panneaux composite	375,4	87,0	88,4
Barres composite avec panneaux composite	274,3	188,1	74,5

Concept technique optimal pour le toit	**Poids (kg)**	**Réduction du poids (kg)**	**Cote globale**
Base de référence – profilés acier/revêtement aluminium	584		100,0
Profilés aluminium/revêtement d'aluminium	290	294	68,5
Profilés aluminium avec panneaux sandwich fibre	254	330	76,9
de verre		330	64,4
Profilés aluminium avec panneaux sandwich aluminium	254		

Tableau 3 : Allégement global de l’autocar attribuable à de nouveaux concepts techniques

Élément	Réduction de poids maximale	
	(kg)	(%)
Toit	330	57
Treillis latéral	188	41
Plancher	390	53
Moyenne	s.o.	50

Tableau 4 : Réduction potentielle du poids des essieux d’autocars

Emplacement de l’essieu	Poids actuel (kg)	Allégement potentiel			
		9 p. 100		20 p. 100	
		Réduction de poids (kg)	Poids (kg)	Réduction de poids (kg)	Poids (kg)
Avant	7 250*	462	6 788	1 026	6 224
Moteur	9 100*	579	8 521	1 287	7 813
Traîné	6 000*	382	5 618	849	5 151

* En supposant que le poids initial est dans les limites établies par le PE.

En admettant que les autocars endommagent deux fois moins l’infrastructure routière que les autobus urbains, les coûts de maintenance de la chaussée pendant le cycle de vie (15 ans) d’un autocar, devraient diminuer de 2,1 M$ et de 4,5 M$, respectivement, selon que les véhicules sont allégés de 9 p. cent ou de 20 p. cent.

Pour une distance totale parcourue d’environ 375 millions de kilomètres par année par l’ensemble des autocars au Canada, les coûts attribuables aux émissions polluantes de ces véhicules pendant leur cycle de vie (15 ans) devraient diminuer de 54,7 M$ et de 121,5 M$, respectivement, selon qu’ils sont allégés de 9 p. cent ou de 20 p. cent.

Un allégement de 9 p. cent entraînerait une diminution d’environ 7,7 millions de kg des émissions de CO_2 par année. Pour toute la durée de vie (15 ans) du parc canadien d’autocars, la réduction totale des émissions de CO_2 serait de 266 millions de kg. Un allégement de 20 p. cent de l’autocar réduirait les émissions de gaz à effet de serre de 591 millions de kg pendant toute la durée de vie du parc.

Le tableau 5 donne une ventilation des économies au chapitre du CCV résultant d’un allégement de 9 p. cent d’un autocar. Ces chiffres englobent l’ensemble des autocars actuellement exploités au Canada. Comme on le voit, les économies globales générées par un allégement de 9 p. cent des autocars sur une période de 15 ans sont évaluées à 127,8 M$. Si un allégement de 20 p. cent était possible, la réduction totale du CCV s’élèverait à quelque 283,5 M$. Il est prévu que les coûts de fabrication pourront être maintenus au niveau actuel.

Tableau 5 : Diminution du coût du cycle de vie d'un autocar en fonction d'un allégement de 9 p. 100 et de 20 p. 100

Élément de coût du cycle de vie	**Diminution de coût (M$)**	
	Allégement de 9 p. 100	Allégement de 20 p. 100
Exploitant :		
Carburant	-47,3	-105,0
Entretien	-23,7	-52,5
Société :		
Infrastructure routière	-2,1	-4,5
Émissions polluantes	-54,7	-121,5
Fabrication	0,0	0,0
Total	**-127,8 M$**	**-283,5 M$**

Le plan proposé pour la phase 2 comprend la sélection des concepts techniques les plus prometteurs pour la fabrication de prototypes. Ces prototypes seront ensuite mis à l'essai afin de vérifier s'ils se prêtent à un développement en vraie grandeur.

Les concepts techniques proposés permettent un allégement important des autocars. L'étude détaillée et la mise en oeuvre de ces concepts dans les autocars généreront d'importantes réductions du CCV, du poids des essieux, des dommages à l'infrastructure routière et des émissions de gaz à effet de serre.

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GLOSSARY OF ABBREVIATIONS AND ACRONYMS

B	Billion
FE	Finite Element
FEA	Finite Element Analysis
FRP	Fibre Reinforced Plastic (fibreglass)
GHG	Greenhouse Gas
GVWR	Gross Vehicle Weight Rating
HSS	Hollow Structural Steel
K	thousand
kg	kilogram
km	kilometre
Ksi	Kips per square inch
Ktonne	Kilo tonne
L/100 km	Litres per 100 kilometres
LCC	Life Cycle Cost
M	Million
mm	millimetre
MOU	Memorandum of Understanding
MPa	Mega Pascals (1 N/mm^2)
mpg	miles per gallon
N	Newton
OEM	Original Equipment Manufacturer
PSI	Pounds per Square Inch
ROM	Rough Order of Magnitude

1. INTRODUCTION AND PROBLEM DEFINITION

1.1 Intercity Bus Weight History

Intercity bus service throughout Canada and the United States has undergone many changes over the life of the industry. The service has progressed through periods of growth and eventual decline, as in the latter half of the 1900s. However, as identified by Statistics Canada [1], in 1997 scheduled intercity bus travel staged a comeback. While not at the passenger levels of the two prior decades, the number of passenger trips was up almost 14 percent from two years before. This is considered to be a result of companies identifying and adapting to consumer demands.

At the same time, companies were looking for ways of making their operations more profitable. With the sources of revenue primarily coming from passenger fees and parcel service, operators recognized that larger buses could potentially generate more revenue. Consequently, 13.7 m (45 ft.) buses were introduced to the market in the 1990s, whereas before the largest intercity buses were approximately 12.2 m (40 ft.) long.

Along with the larger buses came the requirements necessary to meet passenger demands. They included features such as climate control and larger double glazed windows. Manufacturers were also fabricating buses from heavy metals, such as carbon steel for its cost-effectiveness and stainless steel for its corrosion resistance. With the added weight and energy requirements for some of the new features, larger engines were needed to supply the necessary power. Thus, the evolution of the intercity bus has resulted in heavier buses.

The progression of weight of intercity buses from one company is shown in Figure 1.1, where the weights are presented over the past 25 years for buses manufactured by Prévost Car. As shown in this plot, the weight of their buses has steadily increased since 1974. There was a significant jump in weight in the mid 1980s and the introduction of the 13.7 m (45 ft.) buses in the early 1990s saw another significant weight increase. In recent years the “levelling off” has been due to weight reduction initiatives introduced at Prévost.

1.2 Identification of the Bus Weight Problem

Until recently, the weight of intercity buses was not an issue with regulatory agencies, operators and/or manufacturers. However, intercity buses are considered commercial vehicles in both Canada and the United States. As such, they are subject to provincial weight and dimension limit regulations.

In 1988, a memorandum of understanding (MOU) [2] was developed under the auspices of the Transportation Association of Canada. Its objective was to bring greater uniformity to provincial regulations regarding vehicle size and weight. Since operators of intercity buses are subject to provincial regulations, they are affected by the MOU. The weight restrictions developed for intercity buses under the 1988 MOU are shown in Figure 1.2 (from page 24 of the MOU).

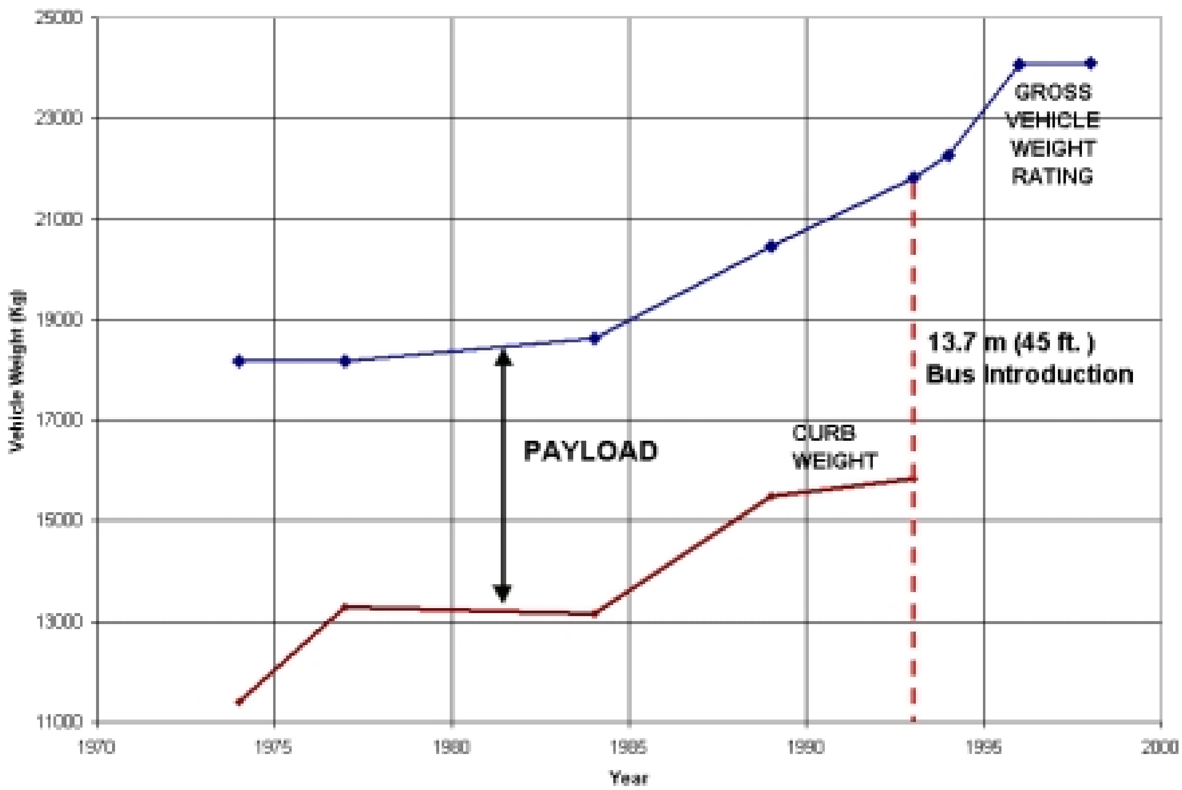


Figure 1.1: Prévost Bus Intercity Bus Weight History

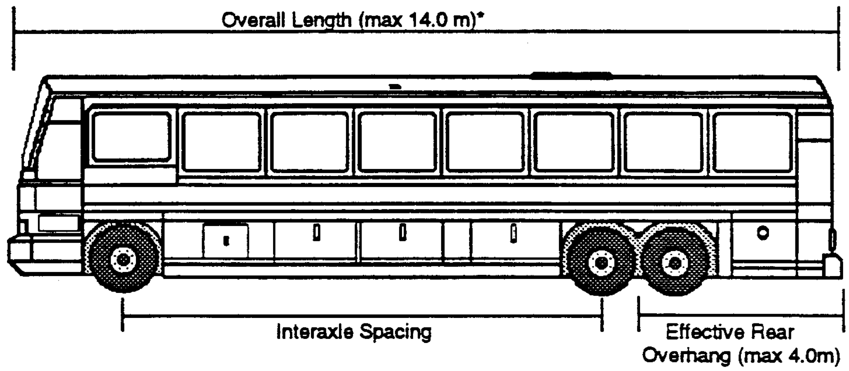
Before this time, the compliance of intercity buses with the regulated weight and dimension limits was not closely monitored. Intercity buses are not routinely required to report to weight scales. The more common way to monitor intercity buses was through random or periodic inspection. However, with buses now being more closely monitored for the MOU limits, there was emerging evidence of problems with compliance. Specifically, two issues emerged:

- Steering axle weight limits:
  During the initial surveys done of intercity buses, out of a total of 140 observations, 50 percent of the buses had steering axle weights exceeding 5,500 kg. (This weight limit was the initial 1988 MOU standard for the front axle.) Furthermore, there was an obvious problem with the regulated load limit per width of tire that is set at a maximum of 10 kg per mm of tire width.

- Drive axle-Tag axle:
  All intercity buses have a drive axle equipped with four tires and a tag axle equipped with two tires. This unique combination of axles in the back is not recognized in Canada as a true tandem axle group since it does not have the same number of tires on each axle. The national standards adopted in 1988 call for a maximum of 9,100 kg on the drive axle and a maximum of 6,000 kg on the tag axle. Out of the 140 observations mentioned earlier, 40 percent of buses had a weight on their drive axle exceeding the 9,100 kg limit.

Category 8: Intercity Bus

Dimensions



*** Note:** If overall length (including bumpers) is greater than 12.5 m., a minimum of 3 axles is required.

Weights

Maximum Gross Combination Weights

2 axles:	13,600 kg
3 axles:	22,500 kg

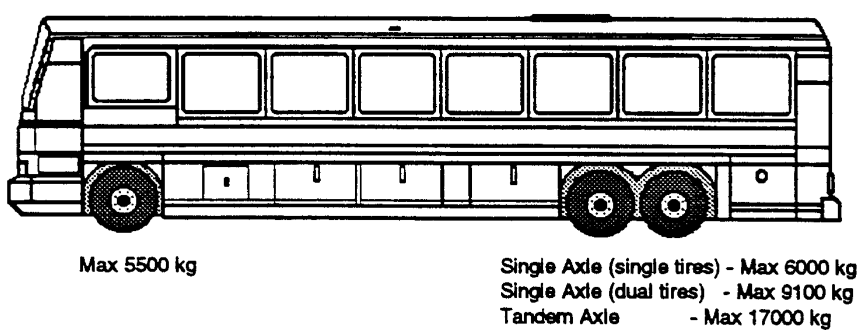


Figure 1.2: MOU (1988) Intercity Bus Limiting Weights and Dimensions

Therefore, the weight problem of intercity buses was regularly being identified as exceeding the regulatory limits.

The original 1988 MOU was amended in 1997. Although the provinces and territories agreed to increase the steering axle weight limit to 7,250 kg from the original 5,500 kg, the tire loading limit of 10 kg/mm and the weight limits of 9,100 kg/6,000 kg for the drive/tag axles remained unchanged.

A new weight survey was conducted in 1999 involving 200 observations. It was found that the compliance with steering axle weight improved. Only 3 percent of the buses exceeded the regulated limit. However, the issue of drive/tag axle limits remained a problem. It was found that 18 percent of the buses had drive axles exceeding the regulated limit of 9,100 kg. Another problem that emerged during this investigation was that some of the axle weights were in excess of the manufacturers' axle rating.

The manufacture of intercity buses was not the centre of attention when the MOU was implemented in Canada. However, with buses regularly exceeding the weight limits, the provinces started to pay special attention to the weight factor. This put pressure on bus operators and manufacturers to solve the growing weight problem. However, intercity bus manufacturers have not been able to provide a simple solution with the existing design because of the requirements for passenger seat spacing, luggage requirements, and the overall structural arrangement of current buses.

As a result, intercity bus operators are left without solutions. Unlike truck operators, they are not capable of significantly changing the load distribution to vary the weight that is carried on the different axles. One important note is that the problem of overloading on the front steering axle has been noticed more frequently with charter operations. With the growth in charter operations as a result of economic deregulation and the weight growth observed in intercity bus designs, the problem will become more serious.

During all of this, bus manufacturers and operators were coming under increasing financial pressure through competition to reduce bus life cycle costs (LCC) while maintaining safety, comfort, and a bus life of about 3,200,000 km (2,000,000 mi) or 15 years. Manufacturers were therefore searching for strategies for reducing the weight of buses that would also pay large dividends in reducing life cycle cost.

In addition, there is an ever-growing concern over the pollutant emissions produced by the transportation industry. While intercity buses comprise a small part of this, heavier buses produce more greenhouse gas (GHG) emissions. Canada's commitment to the 1997 Kyoto Protocol is to reduce GHG emissions by 6 percent below the 1990 levels between the years 2008 and 2012. The government of Canada is actively pursuing ways of meeting these goals. In an options paper produced by the Transportation Climate Change Table [3], the table concluded that no single approach will meet the Kyoto target. Reducing the weight of intercity buses is one of the approaches that can address this problem.

1.3 Potential Solutions

Very recently, bus manufacturers have been using new technologies and materials to reduce the weight of their vehicles. These initiatives have included both complete bus redesigns and selective redesign of bus components in an attempt to produce lightweight buses at costs acceptable to manufacturers and operators.

The success of any of these strategies is determined through an evaluation of the effect of implementing the designs over the complete life cycle of a bus. This is performed through LCC analysis. This evaluation identifies the manufacturing and operating cost changes associated with design modifications. Any improvements in bus design have to be cost-effective for manufacturers and quantified into tangible benefits to the operators, not only in terms of striving to reduce maintenance cost but also in keeping bus acquisition costs to a minimum. Bus operators are extremely sensitive to the initial capital acquisition cost of their buses. This means that the use of high-technology materials and processes will only be viable if manufacturing and material costs provide a better alternative.

1.4 Solution Developed by Prévost Car

One company that has identified the need to reduce the weight of their buses, and has embarked on an extensive multi-year program for this purpose is Prévost Car. In this project, Martec Limited worked very closely with Prévost to identify potential means of reducing the weight of the intercity buses that Prévost produces. This project is considered Phase 1 of a three-phase project as follows:

a) Phase 1: ***Definition*** - In this phase, bus structural components for which potential weight savings could be realized were identified. For each of the identified components, design constraints and requirements were identified. Practical considerations from a manufacturing and cost perspective were also identified. A review of the requirements and restrictions yielded components for which viable weight savings could be realized. For the selected components, weight saving structural design concepts were developed on a conceptual basis. The weight saving methods used were material substitution and/or the application of structural optimization techniques. Materials that were investigated were steel, aluminum, and advanced composites. The selection of the best weight saving methods was performed using a compromise between weight saved and manufacturing and life cycle costs.

b) Phase 2: ***Prototype Design and Testing*** - In this phase, the conceptual designs developed in Phase 1 will be finalized and prototypes for each of these components will be developed and tested.

c) Phase 3: ***Full-Scale Development*** - Using the data generated in Phase 2, full-scale components will be manufactured and tested. Structural testing and/or road trials will be performed as required during this phase. Because of the virtual prototyping performed in Phase 2, prototype manufacturing and testing can now be reduced to one iteration with few or no surprises.

The Phase 1 project started in March 1999 and was completed in January 2000. The results of this work are presented in this report. Section 3 presents the results of a survey where information was gathered from a bus manufacturer (Prévost) and operators to quantify the bus weight problem. Section 4 identifies the areas of the candidate bus that were selected for potential weight reduction. Section 5 presents the results of the analyses to determine the weight reduction concept possibilities for the selected components. The prediction of the potential LCC reduction associated with the lightweight concepts is presented in Section 6, and the selection of the most promising design concepts is provided in Section 7. The proposed work for the follow-on project is provided in Section 8 and the conclusions and recommendations are outlined in Section 9.

2. OBJECTIVES

The objectives of Phase 1 were to:

- develop a practical and sound technical approach to address the bus weight reduction problem;
- select and develop design concepts for components with high potential for weight savings;
- quantify the life cycle cost (LCC) reduction to be gained through a reduced weight bus design; and
- formulate a technical and management approach for the follow-on Phase 2.

3. INTERCITY BUS BACKGROUND DATA

Section 1 provided an introduction to the project and an initial discussion of the problems associated with heavy intercity buses. In this section, an estimation of the magnitude of the problem is presented. This prediction is based upon data collected during the project from government agencies, operators and manufacturers on the costs associated with manufacturing and operating intercity buses. The discussion is presented in terms of the high LCC associated with operating heavy intercity buses, the potential areas of savings with using lighter weight buses, and the limitations on any new design concepts.

3.1 Life Cycle Costs of Intercity Buses

Based on the data collected during the surveys and discussions, the following LCCs were identified:

- manufacturing (including design) costs;
- operating costs (including maintenance);
- infrastructure damage costs; and
- pollutant emissions costs.

The first two of these costs are considered operator LCCs. They include the acquisition (capital) cost and the cost of operating intercity buses. The last two costs are considered societal costs, which have an affect on society as a whole.

Prévost Car staff were contacted to determine the manufacturing cost of current intercity buses. In particular, in order to identify the LCC savings associated with any potential bus weight savings, the manufacturing costs of individual bus components were sought. While manufacturing costs for a complete bus are known, the cost of fabricating individual components was difficult to identify and gather.

Other LCCs, such as the cost of incorporating new design changes, are also difficult to quantify. For example, discussions were held with Transport Canada, Prévost, and operators regarding safety issues related to bus weight reduction and its impact on bus designs. Two areas that were discussed were seat belts and rollover protection.

From preliminary investigation it is expected that seat belts will add to the weight of a bus due to the required hardware and the increased strength requirements for passenger restraint. A yet-to-be-released report from the U.S. National Transportation Safety Board that investigated the safety of school buses and motor coaches is likely to recommend the development of performance standards for occupant protection systems (seat belts, roof strength and others) that would account for frontal, side and rear impacts. It is expected that once these standards are developed, they will be required on all newly manufactured intercity buses. However, Canadian bus manufacturers are reluctant to tackle this issue since there is no current U.S. or Canadian regulation that requires seat belts.

Protection during a bus rollover is an increasingly important issue for passengers and regulatory bodies. While currently not in place, it is anticipated that some requirement to afford passenger protection may be forthcoming. To accommodate this requirement, bus designs will have to be modified for rollover protection. The cost of the necessary modifications is not known. However, if these modifications are considered in any new design modifications to reduce the bus weight, then the cost of rollover protection can be kept to a minimum.

A survey of intercity buses operators was conducted to determine the current LCC of intercity buses and operational benefits that could be gained by developing lighter buses. While data was obtained on operating costs, no information could be gathered from these companies directly related to the effect of weight on these costs. Also, operating costs such as operator/driver expenses, permits, taxes, insurance, licensing, financing, etc., were not collected for this study. These LCC are not affected by the reduction in weight of intercity buses. The operators surveyed were Greyhound Canada Transportation, Saskatchewan Transportation Company, Orléans Express, Grey Goose Bus Line, Ontario Northland, McCulloguh Coach Lines, Badder Bus Service Limited, and Voyageur Corporation.

Greyhound Canada operates approximately 400 motor coaches in Canada and travels approximately 65 million kilometres per year [4]. This is more than 10 percent of the total number of inter-city and charter buses. In terms of mileage, they have roughly 20 percent of the usage in all categories included for an industry total of approximately (65M/0.2) 325M kilometres per year. They spend an average of $8M per year on fuel. Based upon these numbers, the complete intercity bus industry in Canada is expected to spend approximately $40M ($8M/0.2) on fuel per year for 325M km travel.

This is less than that predicted in a report from the Transportation Table on National Climate Change [5]. In this report, it was estimated that a combination of scheduled and charter services in Canada resulted in 425M km travel. At 39 L/100 km (from Reference 5) and at a price of $0.60/litre, this translates into a fuel cost of approximately $100M per year. From these two sources, the range of fuel costs is predicted to be between $40M and $100M. For the purposes of this report an average of these two values will be used, i.e. $70M at 375M kilometres. With an average of approximately 4,000 intercity buses in active service in Canada [5], this works out to be approximately $17,500 per bus for fuel costs. The total fuel costs for an individual bus and the complete Canadian fleet of buses over the 15-year economic life are $262.5K and $1.05B, respectively.

In addition, information as provided in Reference [6] estimates that maintenance costs account for approximately 10 percent of operating expenses, which is approximately equal to the fuel costs. Therefore, assuming that the relationship between maintenance costs and fuel costs holds, maintenance costs for the complete Canadian intercity bus fleet over the economic life of the buses are approximately $1.05 B.

The estimated LCC associated with infrastructure damage is based upon the information in Reference 7, where it is predicted that reducing the weight of an urban bus by 10 percent results in a saving on road infrastructure damage of $0.012 per bus kilometre. Assuming a linear relationship between dollars saved and weight saved, that 100 percent of weight saved equals the total possible infrastructure damage, and that intercity bus damage is approximately 50 percent as severe as urban bus damage, then the estimated fleet yearly LCC is $22.5M. This is based upon 375M kilometres per year.

One important LCC of intercity buses is the cost associated with the damage inflicted upon the environment from generated pollutants. Statistics from the Transportation Table report [5] show that in Canada intercity buses use approximately 166 million L of fuel per year (1995 levels). This produces 459 million kg of CO_2 (based upon 2.764 kg CO_2 generated per litre of fuel burned) which contributes to the greenhouse (GHG) gas emission problem. From Reference [7], it is estimated that a 20 percent urban bus weight reduction translates into a saving on pollutant emissions of $0.0216 per bus kilometre. These costs are based upon costs of measures that have to be put in place to eliminate, mitigate, or reduce the quantity of pollutants released. If it is assumed that this is equally true for intercity buses, then the cost of pollutant emissions is estimated at ($0.0216/0.2) $0.108 per bus kilometre. Based upon the estimated 375M total bus kilometres per year, the total LCC for pollutant emissions is estimated at $40.5M per year.

The fabrication cost of one intercity bus is estimated at $300K. This is based on information provided by Prévost Car on intercity bus selling prices. The fabrication cost of Prévost Car's buses is confidential. However, the selling price of an intercity bus was provided at approximately $490K. From this, it is assumed that the fabrication cost is 60 percent of the selling price. The fabrication cost of the bus is considered constant over the life cycle of the bus.

A summary of the estimated LCC of current intercity buses is presented in Table 3.1. The costs are presented as operator and societal costs for one intercity bus over its life (15 years), the complete Canadian fleet of intercity buses (4,000 buses) for one year and the complete Canadian fleet of intercity buses for 15 years.

Table 3.1: Intercity Bus Life Cycle Cost

Life Cycle Cost Component	Individual Intercity Bus Cost (15 years) $K	Intercity Bus Fleet Cost (1-Year) $M	Intercity Bus Fleet Cost (15 years) $M
Operator:			
Fuel	262.5	70.0	1,050.0
Maintenance	262.5	70.0	1,050.0
Societal:			
Road Infrastructure	84.4	22.5	337.5
Pollutant Emissions	151.9	40.5	607.5
Fabrication	300.0	1,200.0	1,200.0
Total	**$1,061.3**	**$1,403.0**	**$4,245.0**

3.2 Potential Areas of Savings

From the gathered data on intercity bus manufacturing and operational expenses and the expected areas of saving from lighter weight buses, a list of the main thrusts in producing lighter intercity bus designs was developed:

i. decreased operating costs;
ii. decreased maintenance costs;
iii. decreased greenhouse gas emissions; and
iv. decreased infrastructure damage.

It is not expected that any significant savings are possible in the manufacturing costs.

3.3 Design Limitations

In defining the problem, it is also important to know of possible limitations in the solution. Therefore, information was gathered on production and design constraints related to bus weight reduction. This was gathered through interviews with Prévost Car personnel. Technical staff were consulted for their opinions as to which areas carry the highest potential for weight reduction and their views of the more important constraints/problems that are expected in developing a new lightweight concept design.

These are summarized as follows:

- it was deemed important to have new concepts that integrate easily into existing production methods. Major design changes would have to be incorporated over many years;
- aluminum provides a very high potential for weight reduction; however, major concerns about possible corrosion problems on components near the road surface would have to be addressed; and
- polycarbonate (Lexan) windows offer high weight savings potential; however, scratch resistance, UV protection and static charge resistance are concerns.

4. WEIGHT REDUCTION CANDIDATE SELECTION

With the intercity bus weight problem defined, a methodology was required that would determine the lightest weight concept designs that would be the most viable for incorporation into current manufacturing processes. The methodology that was chosen first involved the identification of intercity bus components with the highest potential for weight reduction. A series of analyses was then performed on these components to develop new lightweight concept designs.

To carry out the design concept development, a representative intercity bus had to be chosen. The candidate bus chosen for this study was the Prévost Car LeMirage XLII model. The XLII model is the next generation of the Prévost LeMirage XL model, which has been the workhorse of Prévost's coaches for more than three decades. The XLII takes advantage of the superb structural integrity qualities derived from the XL, as well as the advanced technology of the Prévost H-series premium touring coaches.

The XLII was chosen for this study since it is a new generation model. Any design modifications to reduce the weight can be incorporated early in the bus design life, thus providing long-term benefits to manufacturers and operators. This bus is also typical of intercity and charter buses operating within Canada.

In order to select the most promising bus components for concept design, it was necessary to know the configuration and weight of each XLII bus component. This was important because if a particular component looked promising in terms of weight reduction, but its total weight was a fraction of the complete bus weight, the overall savings would be insignificant. In that case, the component was not considered as a design candidate.

A list of all of the bus components and their weights is shown in Table 4.1. It can be seen that the exterior finish is 6.6 percent of the total bus weight. The windows are approximately half of this, which comprises about 3 percent of the bus weight. The interior finish is approximately 28 percent of the total bus weight; however, the passenger weight is included in this component, which comprises 20 percent of the weight. Therefore, the interior finish (excluding passengers) is approximately 8 percent of the total bus weight. The most significant parts of this weight are the parcel compartment (overhead) and the passenger seats.

The baggage (luggage) compartment weight comprises mostly fuel (3 percent) and luggage (7 percent). The remaining parts are insignificant with respect to the total bus weight. The motor/mechanicals account for approximately 12 percent of the total bus weight. The suspension and structure are very significant at about 14 percent and 17 percent, respectively. And finally, miscellaneous body parts account for approximately 10 percent of the total weight.

The most significant components in terms of proportion of the overall bus weight are highlighted in Table 4.1. Of these, the components considered most suitable for new/different material and alternative configurations are the windows, parcel compartment, the seats, and the structure. The motor/mechanicals and the suspension were not seriously considered for weight reduction at this time, since they are very specialized and are purchased as assembled units. A secondary weight savings will be achieved simply by reducing the weight in other areas of the structure (i.e., a lighter bus will require a smaller engine that is lighter than a large engine). The miscellaneous parts were not considered.

Table 4.1: Prévost Car XLII Bus Components and Weights

Component Name & Parts	Weight (kg)	Total (kg)	Percentage of Total Component	Percentage of Total Bus
Exterior Finish		1409.5		6.6
Doors, front bumper, front face	323.7		1.5	
Windows	686.2		3.2	
Baggage doors	163.3		0.8	
Rear face	29.9		0.1	
Motor cover	81.2		0.4	
Rear bumper	25.9		0.1	
Evaporator door, service doors	99.3		0.5	
Interior Finish		6077.7		28.4
Dashboard	89.8		0.4	
Defrost unit	45.8		0.2	
Drivers seat	115.7		0.5	
Parcel compartment	531.5		2.5	
Passengers	4382.1		20.5	
Passenger seats	881.9		4.1	
Toilet	30.8		0.1	
Baggage Compartment		2423.8		11.3
A/C ventilation	172.4		0.8	
Gas tank	93.4		0.4	
Fuel	661.1		3.1	
Luggage	1496.9		7.0	
Motor Compartment		2582.0		12.1
Motor and mechanicals	2582.0		12.1	
Spare Tire Compartment		169.6		0.8
Spare tire, gear box, Pitman arm	169.6		0.8	
Suspension		2953.8		
Differential	1360.8		6.4	
Tag axle	680.4		3.2	
Rigid axle	912.6		4.3	
Structure	3628.7	3628.7	17.0	17.0
Body & Accessories		2120.8		9.9
Miscellaneous body parts	2120.8		9.9	
TOTAL	21368.6	21368.6	100.0	100.0

The structure was deemed to have the greatest potential for weight reduction. It is 17 percent of the total weight of the bus and hence any significant structural weight reduction translates into a significant overall weight reduction. Therefore, the structural component was chosen for alternative lightweight intercity bus concept design.

Some consideration was given to studying the parcel (overhead) compartment and seats for potential weight reduction. Extrusion and/or pultrusion methods using composite materials were discussed for methods of reducing the weight. More exotic materials, such as titanium and magnesium, were identified as potential materials to make the seats lighter. However, it was decided to undertake a more global initiative for looking at weight reduction by studying the bus structure.

5. WEIGHT REDUCTION APPROACH

This section outlines the approach to develop new lightweight concepts of the structural components of intercity buses. The methodology used in the development of these concepts is first described. The details of the concept development for each structural component are then presented, along with the results of an investigation looking at the additional weight savings of combining the effects of individual design concepts. Finally, based upon the intercity bus life cycle costs, concepts are selected for identifying the highest potential for weight savings.

5.1 Analysis Methodology

The methodology used in the development of the design concepts is based on an investigation of each of the individual structural components for potential weight savings. This is performed through an analysis of the components using both new materials and/or new configurations.

The structural evaluations are performed using a finite element (FE) model of a typical intercity bus. The model chosen for this work is the Prévost Car XLII, a 13.7 m (45 ft.) bus that offers both coach and motor home configurations. A plot of the FE model of this bus is shown in Figure 5.1.

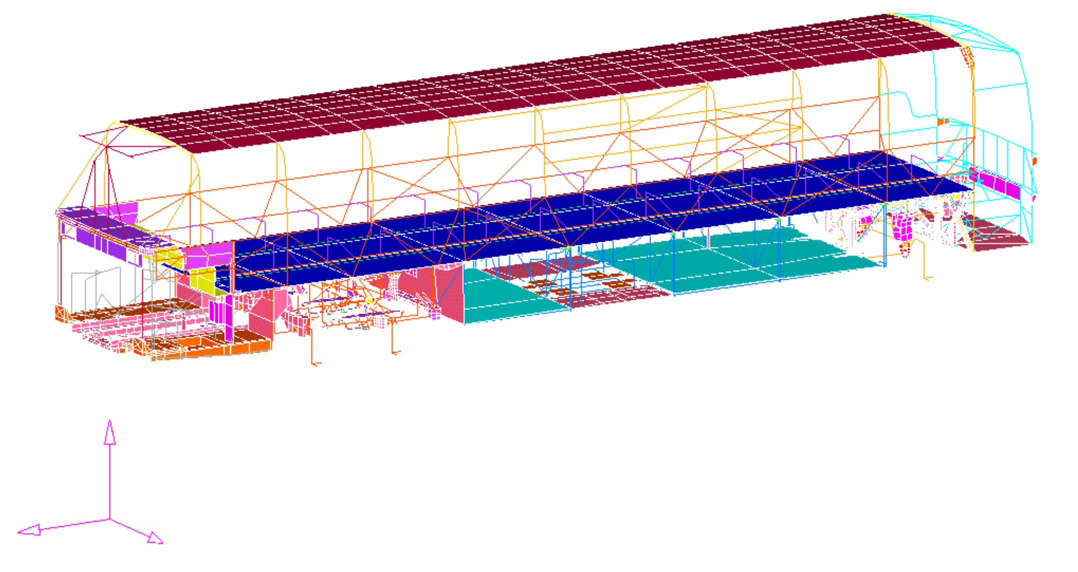


Figure 5.1: FE Model of the Intercity Bus

The model consists of a combination of two-node beams and four-node shells that are used to represent the structural components of the bus. All non-structural mass is represented by mass elements concentrated at the centroid of the actual equipment mass.

An analysis of the bus model was first performed in the original configuration to determine the baseline structural response of the roof, floor, and side truss. The baseline responses that were considered important were the structural stiffness and the member stresses. The stiffness was measured through the deflection of the structure and the basis for development of the concept designs was to maintain deflections near the baseline value for any of the new concept designs. Stresses had to be kept within the design limits (as specified in the next section).

Following the establishment of the design baselines, each component was modified for a new material and/or configuration. These new concepts were then evaluated for potential weight reduction, involving an iterative process of concept design modification to provide a final design that matched the original stiffness and maintained the stress levels within the design criteria.

5.2 Applied Load and Design Criteria

The design loads for the XLII bus were used for the intercity bus weight reduction study. These loads are a series of overall vertical bending, lateral bending and torsion loads that define the regime of loads to which an intercity bus would be exposed during operation. However, Prévost Car has found that the vertical bending load is almost always the critical load condition. Therefore, this load is used as the primary criterion in the analysis/development of the design concepts for bus weight reduction.

The magnitude of the vertical bending is 3.0 g downward and represents the physical scenario of a bus travelling over a large bump in the road. The only structural component that has design concepts developed using a load different from the vertical 3.0 g load is the roof. Details of the loads used for this component are presented in Section 5.3.1.

The design criterion that is used for the analyses performed in this study is to match the stiffness of the original component. At the same time the stress levels in the bus structural material must stay below 90 percent of the yield strength of the material – when subjected to the design load.

5.3 Design Concepts

The design concepts developed in this study are new lightweight designs of the side truss, the roof, the floor, and the windows. The details of the development of these concepts are presented in the following sections.

5.3.1 Roof Weight Reduction Concepts

The current roof configuration for the intercity bus chosen for this study is shown in Figure 5.2. It consists of a series of transverse stainless hollow structural steel (HSS) ribs covered by a ceiling. The ceiling consists of an aluminum skin stiffened by longitudinal stainless steel beams. Windows are located between each of the ribs. Every second window is hinged for emergency egress and is therefore considered non-structural. All other windows are fixed to the surrounding structure and are therefore capable of carrying a structural load. The structural windows are modelled by diagonal beam elements between each of the ribs.

The gross weight of the current roof configuration is 1,692 kg with the structural members weighing 584 kg. The non-structural weight of 1,108 kg consists of wiring, equipment, and non-structural windows.

The criterion used in the development of new design concepts for the roof structure is to match the local stiffness of the structure based on top and side rollover scenarios. The modelling was performed by isolating the roof structure from the overall bus structure as shown in Figure 5.2. As shown in this figure, the boundary conditions for this model are applied to the bottom of the ribs where the ribs are attached to the side trusses.

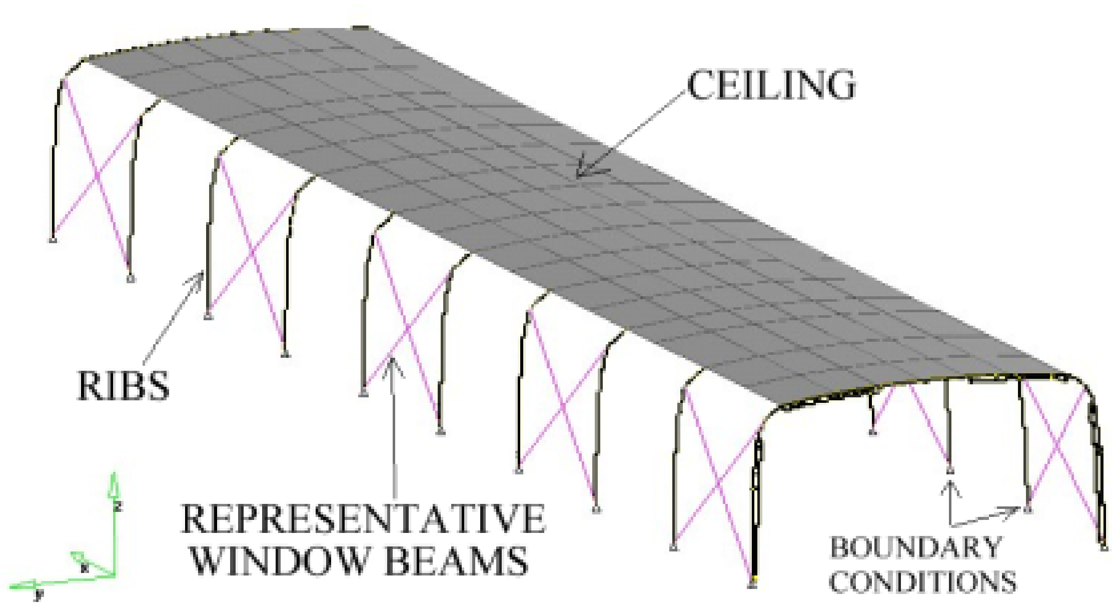
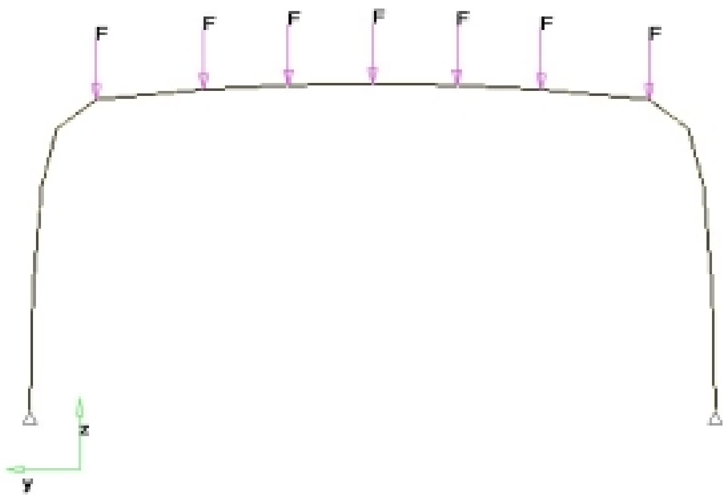


Figure 5.2: FE Model of the Intercity Bus Roof Structure

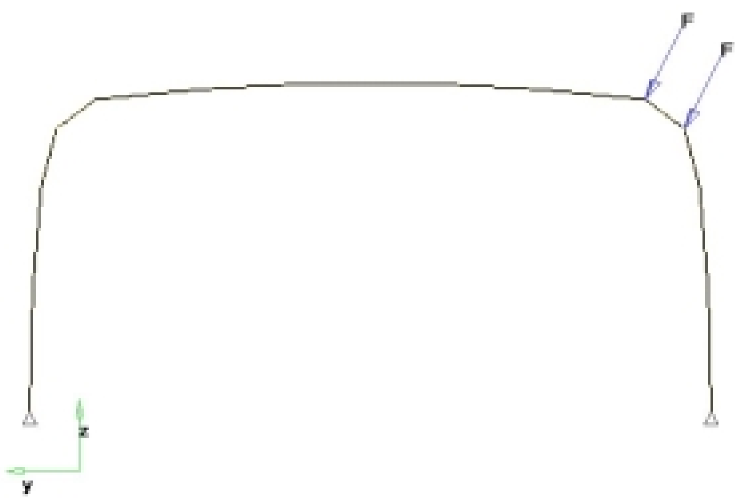
The stiffness components that are important in developing new roof design concepts include: the bending of the ribs, the shearing/bending of the ceiling between ribs, and the global stiffness of the roof.

The applied loads used to represent the two rollover load cases are uniform loads of 1.5 times the total bus weight. This load factor was chosen from the National Highway Traffic Safety Administration Standard for top and side rollover of buses [9]. These loads are applied to the FE model as shown in Figure 5.3.

Three design concepts were investigated for the roof structure. They are summarized in Table 5.1 along with the current (reference) configuration. All three design concepts use aluminum ribs to replace the current steel ribs. The first design concept has the skin structure fabricated from aluminum, the second concept uses a fibreglass composite skin, and the third concept uses an aluminum composite skin.



(a) Top Rollover



(b) Side Rollover

Figure 5.3: Applied Rollover Loads for the Intercity Bus Roof FE Model

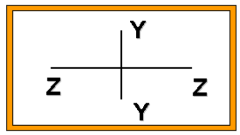
Table 5.1: Intercity Bus Roof Design Concepts

Design Concept	**Specifications**	**Fabrication**
Reference	Ribs: stainless steel beams Ceiling: stainless steel beams and aluminum skin (16 Ga)	Welded and riveted joints
1	Ribs: bent aluminum tubing Ceiling: aluminum tubing (same configuration as reference) and same aluminum skin (16 Ga)	Welded and riveted joints
2	Ribs: bent aluminum tubing Ceiling: fibreglass sandwich panels	Bonded and riveted joints
3	Ribs: bent aluminum tubing Ceiling: aluminum sandwich panels	Bonded and rivet joints

The specifications for the beams used to fabricate the ribs are shown in Table 5.2. The relative stiffness of the proposed beam as compared to the current (reference) beam is presented. The forward stiffness of the "new" rib beam is 70 percent of the current while the lateral stiffness is 120 percent of the current. The higher lateral stiffness is required to keep the beam stresses below the design limit for the lateral rollover condition.

Since the proposed beams are made of aluminum, there is a considerable weight savings over the current steel beams. Each current rib weighs 23 kg while a proposed aluminum rib weighs only 12 kg.

Table 5.2**:** Intercity Bus Roof Rib Member Properties



BENDED TUBING 64 mm x 90 mm x 3.2 mm

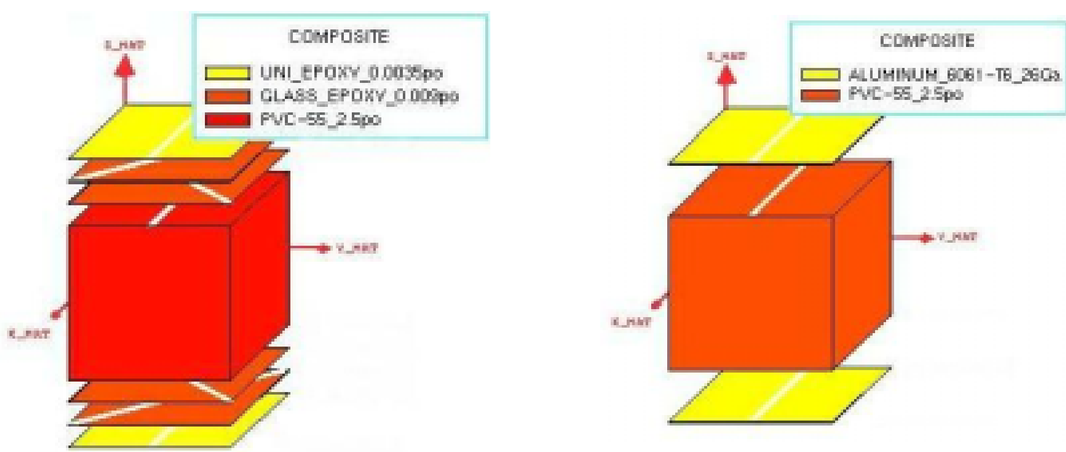
MATERIAL: AL6061-T4

S_{ut} = 210 MPa (30 ksi) GOOD FORMABILITY

S_y = 110 MPa (16 ksi) AND WELDABILITY

RIB	MASS (Kg)	BENDING STIFFNESS FORWARD $(EI)_{yy}$	LATERAL $(EI)_{zz}$
REFERENCE RIB	23	1	1
NEW RIB	12	0.7	1.2

The proposed sandwich panel construction for the fibreglass and aluminum composite panels is shown in Figure 5.4 (a) and (b), respectively. Both design concepts use a PVC-55 core. The composite outer skin is a fibreglass/epoxy layup. The outer skin of the aluminum sandwich panel is fabricated from 6061-T6.



(a) Fibreglass (b) Aluminum

Figure 5.4: Proposed Intercity Bus Composite Roof Panel Construction

A proposed connection detail for joining the sandwich panels to the ribs is shown in Figure 5.5. This plot shows a cross-section of the rib and sandwich panel. The sandwich panel skins are bonded to the outside of the ribs with the core abutting the side of the rib. The sandwich panels can either be fastened or bonded to the ribs.

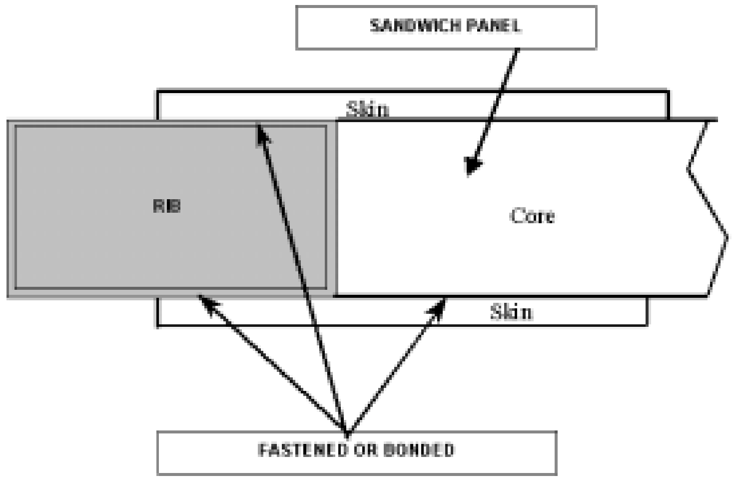


Figure 5.5: Connection Details of the Intercity Bus Roof Composite Panels to the Ribs

FE models of the original configuration and for each of the design concepts were developed and analysed for the side rollover and top rollover load conditions. The displacement at each of the rib locations was determined from these analyses.

For the top rollover condition, the vertical displacement component is most important in considering the stiffness of the ribs. The vertical displacement results at the top of each rib from the analysis for the top rollover load case is shown in Figure 5.6.

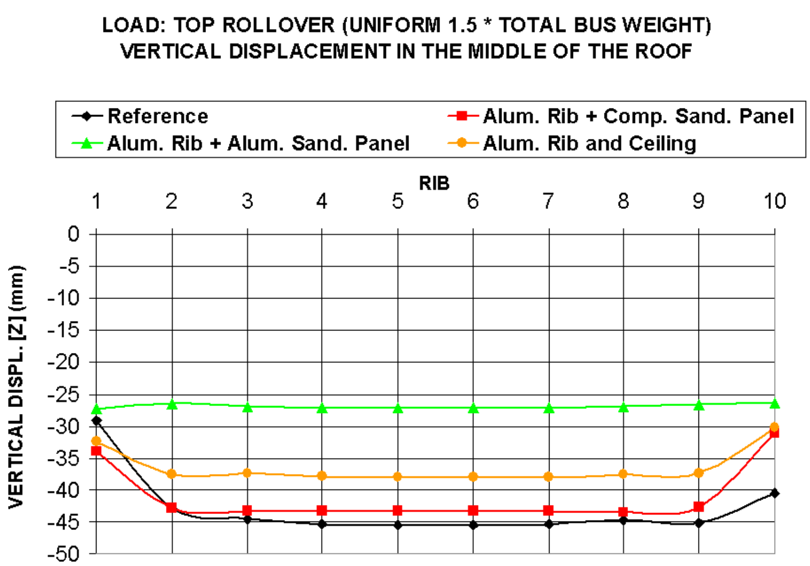


Figure 5.6: Vertical Displacement of the Intercity Bus Roof Design Concepts for Top Rollover

As shown in this figure, all of the design concepts have a smaller displacement and hence are stiffer than the current design. The aluminum rib/aluminum sandwich panel is the stiffest of the design concepts.

In the side rollover load case, the lateral displacement component is the most important displacement component for consideration of stiffness. The FE models (original and new concepts) were analysed for the side rollover condition with the lateral displacement results of these analyses shown in Figure 5.7. Similar to the top rollover case, all design concepts have smaller displacements than the current configuration and are therefore stiffer than the current configuration.

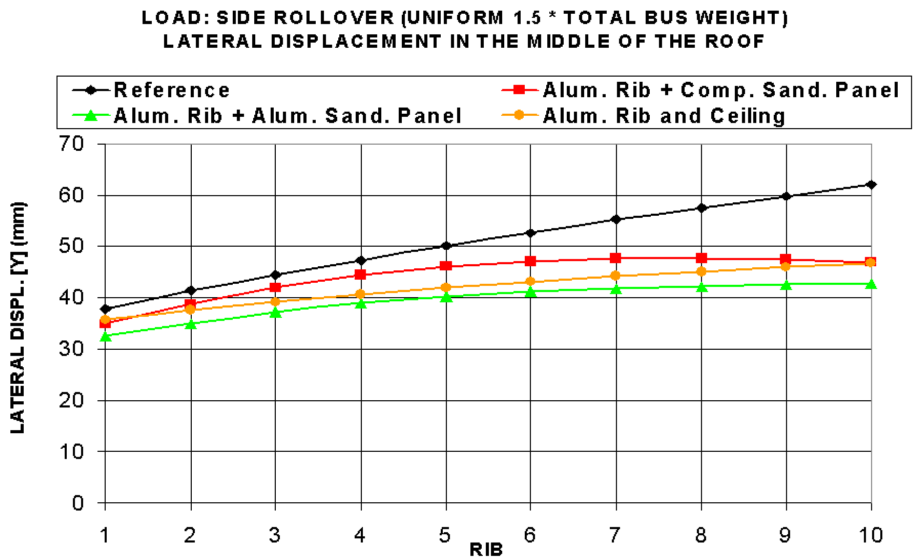


Figure 5.7: Lateral Displacement of the Intercity Bus Roof Design Concepts for Side Rollover

The stresses in the ribs and in the panels determined from the FE analysis for each of the design concepts are presented in Table 5.3. These values are presented as a percentage of the ultimate stress of the material. The design concepts that use the 6061-T6 aluminum are either at or below the stress level of the current configuration. These stresses are less than 83 percent of the material ultimate strength for the top rollover load case and less than 125 percent of the material ultimate strength for the side rollover load case.

The member stresses for the side rollover load case are shown to be above the ultimate strength of the material. In this analysis, the goal was to match the stiffness of any new design concept to the original (reference) configuration, which was achieved. The stress predictions are approximate since an impact analysis is required to accurately determine the member stresses. In that case, a more accurate determination of the loads applied to the structure upon impact would be determined.

The goal of this analysis was to keep the stresses at or below the current member values. It is possible that the member sizes may have to increase for a detailed design of the roof for impact considerations. However, some plasticity may be permitted as long as the required passenger protection space is not violated. Therefore, 125 percent of yield may be a possible design limit for a bus rollover condition.

Table 5.3: Stress Levels in the Intercity Bus Roof Design Concepts

DESIGN	SPECIFICATIONS	PERCENTAGE OF THE ULTIMATE STRESS			
		TOP ROLL		SIDE ROLL	
		RIB AL6061-T4	RIB AL6061-T6	RIB AL6061-T4	RIB AL6061-T6
Ref.	Ribs: stainless steel beams Ceiling: stainless steel beams and aluminum skin (16 Ga)	96		125	
1	Ribs: bended aluminum tubing- Ceiling: aluminum tubing (same configuration as reference) and same aluminum skin (16 Ga)	115	83	172	125
2	Ribs: bended aluminum tubing Ceiling: fibreglass sandwich panels	115	83	172	125
3	Ribs: bended aluminum tubing Ceiling: aluminum sandwich panels	100	72	161	118

Summary of Results for the Roof Design Concepts

The weight reduction potential for each of the roof designs is presented in Table 5.4. From the results, it can be seen that all of the design concepts have a potential of at least a 50 percent structural weight savings, and an overall 20 percent mass reduction. The hybrid construction with aluminum ribs and sandwich panels is very light and requires no welding. It is suitable for riveted or bonded connections.

Table 5.4: Weight Reduction Potential of the Intercity Bus Roof Concept Designs

DESIGN	SPECIFICATIONS	WEIGHT SAVED (percent)	
		Gross	Structural
Ref.	Ribs: stainless steel beams Ceiling: stainless steel beams and aluminum skin (16 Ga)	-	-
1	Ribs: bended aluminum tubing Ceiling: aluminum tubing (same configuration as reference) and same aluminum skin (16 Ga)	17	50
2	Ribs: bended aluminum tubing Ceiling: fibreglass sandwich panels	20	57
3	Ribs: bended aluminum tubing Ceiling: aluminum sandwich panels	20	57

Further gross mass reduction is possible with the roof design through the utilization of polycarbonate (Lexan) windows. As noted in Section 3, polycarbonate windows have had inherent problems with ultraviolet (UV) protection and are susceptible to scratches and static charge. Products are now available that offer solutions to these problems.

In addition to this, the rib strength can be further improved through the use of high strength aluminum. For the side rollover condition, the design concepts match the current configuration stress levels at 125 percent of ultimate strength. However, these stress levels can be reduced through higher strength aluminum. While not affecting the stiffness of the ribs, a higher strength material would reduce the stresses such that they would be less than the ultimate strength.

5.3.2 Side Truss Weight Reduction Concepts

The current side truss configuration on the intercity buses chosen for this study is shown in Figure 5.8. There are two matching trusses on either side of the bus with the truss members consisting of welded mild HSS sections. The total weight of both trusses is 462 kg or 231 kg per side. The trusses carry the overall bending load of the bus. This load is carried through compression in top rail, tension in lower rail, and shear stresses are carried through the truss diagonals.

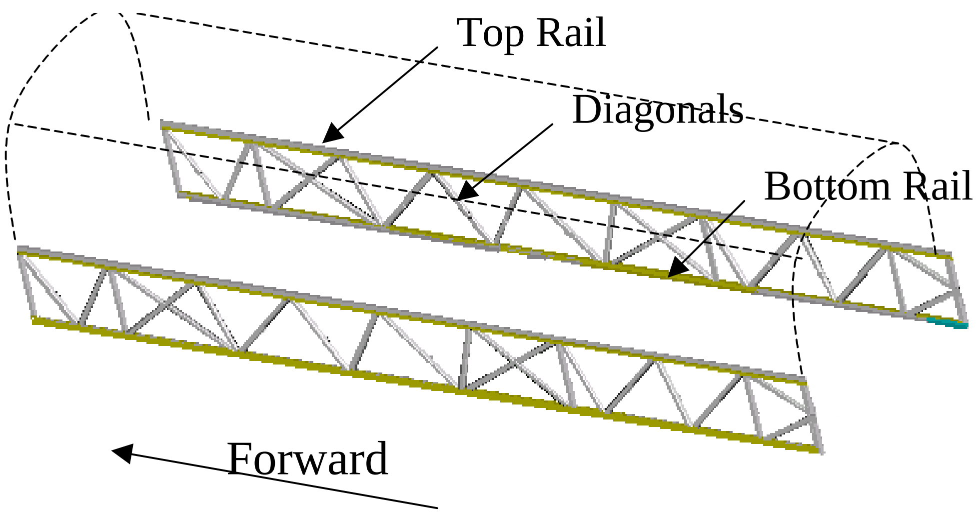


Figure 5.8: Prévost Car XLII Intercity Bus Current Side Truss Configuration

The concept designs for a lightweight side truss involve a combination of material changes and configuration changes. The new material design consists of replacing the existing steel design with aluminum. The new configurations involve replacing the truss design with a sandwich panel design as shown in Figure 5.9. This design has an outer and inner skin with a foam core (similar to that in Figure 5.4(b)) and a perimeter beam for attaching the truss to the floor and roof structural members.

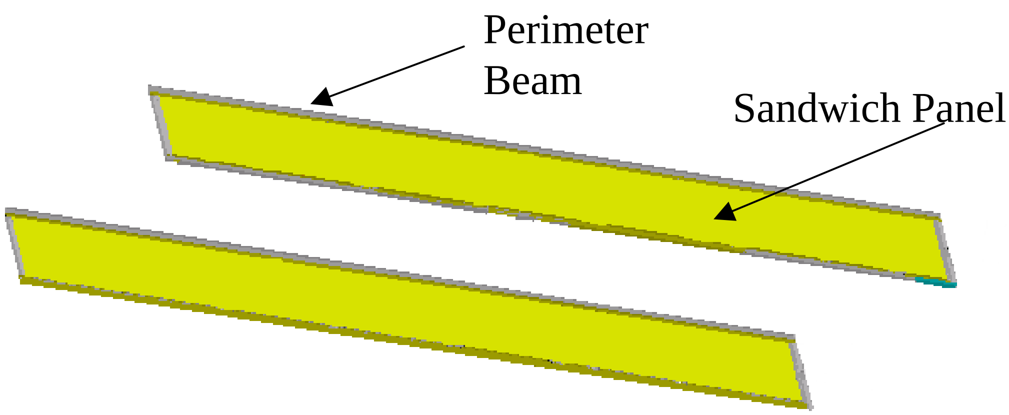


Figure 5.9: Intercity Bus Proposed Lightweight Side Truss Configuration

Six different design concepts were considered for the side truss. A summary of these lightweight designs is presented in Table 5.5. FE models were developed for the original and six concept designs and these models were analysed using the design loads.

Table 5.5: New Materials/Configurations Studied for Intercity Bus Side Truss Design Concepts

Reference No.	Design Concept
1	All aluminum truss with same configuration
2	Steel sandwich panel, steel top and bottom rails
3	Aluminum sandwich panel, aluminum rails
4	Composite sandwich panel, aluminum rails
5	Composite sandwich panel, steel rails
6	Composite sandwich panel composite rails

The results of the FE analysis of the six design concepts for the 3.0 g vertical load are presented in Figure 5.10. This plot shows the displacement along the bottom of the side truss from the front to the rear of the bus. As noted in Section 5.1, one of the design criteria for the new concepts is to match the stiffness of the original configuration. This is accomplished in the side truss by maintaining the same deflection at the bottom of the side truss.

Designs 2 and 5 are the stiffest, the aluminum truss (Design 1) is the least stiff, and all other concepts have approximately the same stiffness as the original steel truss. All designs are relatively stiff with a range of maximum displacement in the passenger compartment from 4 to 7 mm.

For the aluminum truss concept, all other stress members were within the design limit of 90 percent of yield of the material. For the sandwich panel designs, the maximum shear stresses were all below 60 MPa, which is also within the design limits.

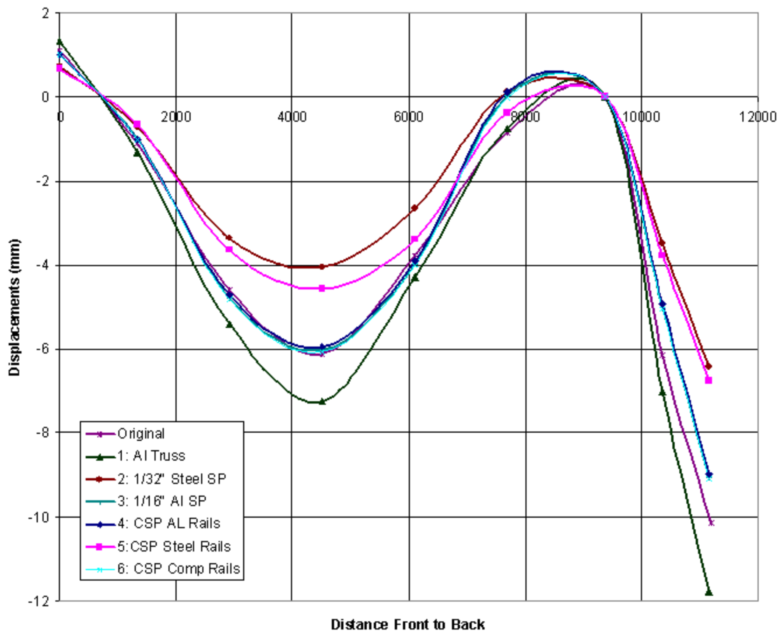


Figure 5.10: Deflection Results of Intercity Bus Side Truss Design Concepts

Summary of Results for the Side Truss Design Concepts

A detailed summary of the results of the analysis of the different truss configurations is presented in Table 5.6. This table presents the weight savings (in kilograms and percentage) of each of the design concepts.

From this table it is seen that the change to an all-aluminum truss using the original truss configuration saves 92 kg (20 percent). However, the best weight savings is with the sandwich panel constructed from either aluminum or fibreglass. In this case, a weight reduction of up to approximately 180 kg (40 percent) is achieved.

All of the design concepts have stresses within the design limits and match very well with the original truss stiffness. The maximum vertical displacement at the bottom of the side truss from any of the design concepts is 7 mm and the minimum is 4 mm. These are all very close to the original displacement of 6 mm.

In addition to the weight savings shown in Table 5.6, further weight reduction potential is possible if the exterior web plate can be used as the finished panel.

5.3.3 Floor Weight Reduction Concepts

The current floor configuration on the intercity bus chosen for this study is shown in Figure 5.11. This structure consists of transverse (lateral) beams that are used to support a plywood floor (which has been removed from the plot for clarity). The plywood floor transfers the passenger load to the transverse beams and provides shear stiffness for the floor structure. The load from the transverse beams is transferred to the two longitudinal support beams which also carry the load of the luggage compartments and the fuel tank. All of the floor structural members are steel with the total weight of the floor (including the plywood) being 740 kg.

Table 5.6: Summary of Intercity Bus Side Truss Concept Designs

	CONFIGURATION	WEIGHT SAVINGS (kg)	WEIGHT SAVED (percent)
	Original design – steel truss - steel top and bottom "rails" - steel shear members - steel vertical end members	**N/A**	**N/A**
1	Aluminum truss - aluminum top and bottom rails (2" area) - aluminum vertical end members - aluminum tubular shear members (3" area) - aluminum seat rail	**92.1**	**20**
2	Replace truss diagonals with metal/foam/metal plate - steel top and bottom rails - 1/32" steel plate for shear web - steel vertical end members - eliminate seat rail	**49**	**11**
3	Replace truss diagonals with metal/foam/metal plate - aluminum top and bottom rails (2" area) - aluminum vertical end members - 1/16" aluminum plate for shear web - eliminate seat rail	**177.1**	**38**
4	Replace truss diagonals with composite panel - aluminum top and bottom rails - aluminum vertical end members - composite panel for shear web - eliminate seat rail	**179.1**	**39**
5	Replace truss diagonals with composite panel - steel top and bottom rails - steel vertical end members - composite panel for shear web - eliminate seat rail	**87**	**19**
	Composite rails and shear panel - composite top and bottom rails - aluminum vertical end members - composite panel for shear web - eliminate seat rail	**188.1**	**41**

Two new concepts were studied for the floor. The first concept is shown in Figure 5.12.

This concept consists of a composite structural floor that transfers the floor load directly to the longitudinal beams. Hence, the plywood floor is replaced by a structural floor that does not require the transverse beams for support. Therefore, the transverse (lateral) beams are removed as shown by the red members in Figure 5.12. In addition to this, the structural floor provides very high in-plane stiffness, thus eliminating the need for the cross bracing between the transverse beams. The weight reduction potential for this configuration is a result of utilizing a structural floor that does not weigh significantly more than the plywood floor, but now performs a multiple role. This enables a significant weight reduction through removal of the transverse structural beams.

The second concept includes the modifications of the first concept, but in addition to removing the transverse beams, the longitudinal structural beams are also eliminated. This concept is shown in Figure 5.13.

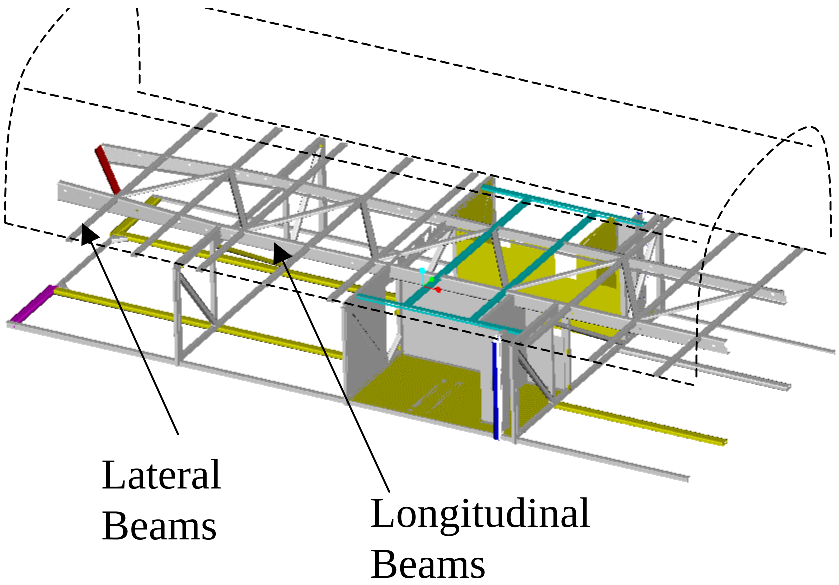


Figure 5.11: Current XLII Intercity Bus Floor Configuration

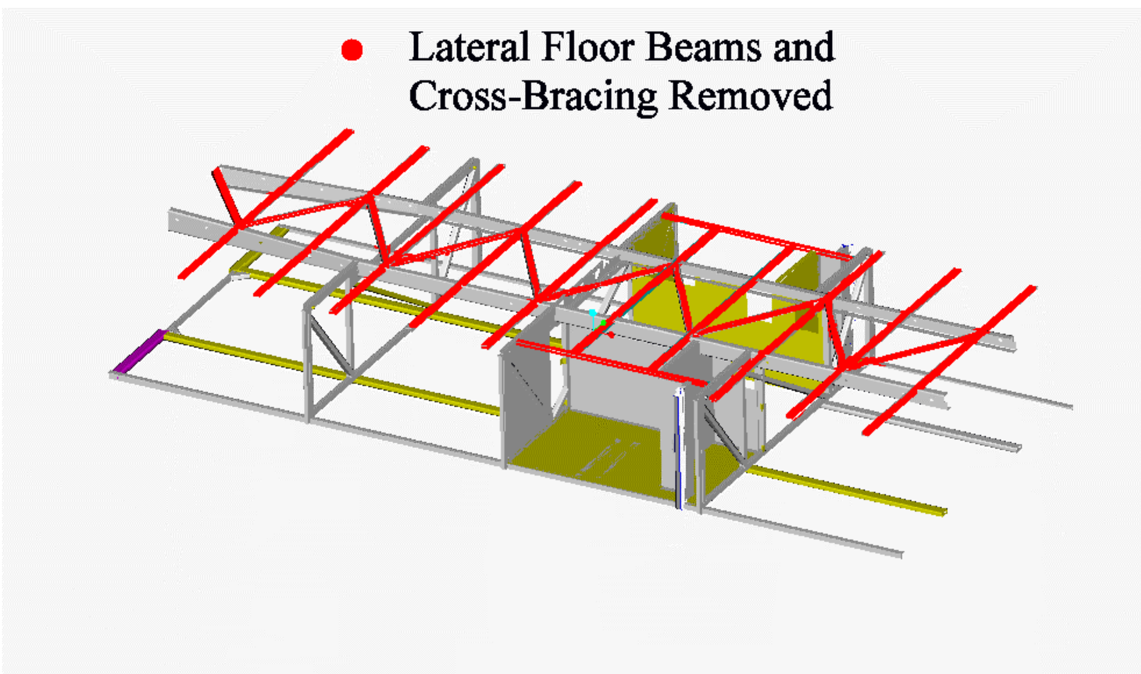


Figure 5.12: Intercity Bus Floor Concept Design 1

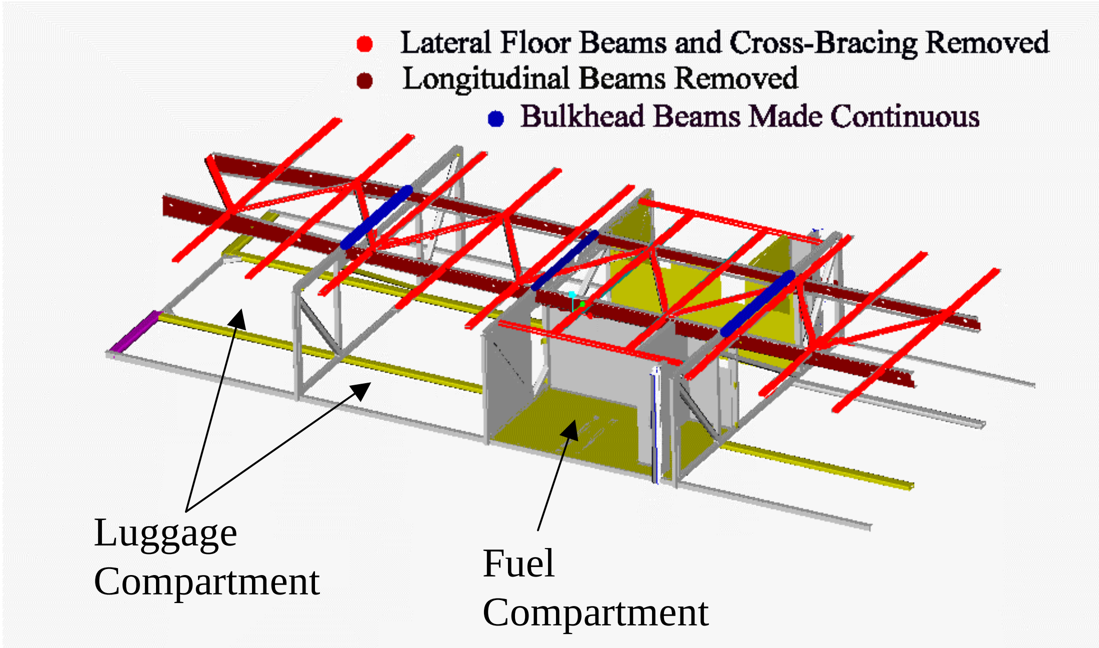


Figure 5.13: Intercity Bus Floor Concept Design 2

In this concept, the luggage compartment loads and the fuel compartment loads are transferred directly to the side truss instead of the longitudinal beams. This enables elimination of the longitudinal beams as indicated by the colour brown. In order for the luggage and fuel compartment loads to be carried directly by the side trusses, the transverse bulkheads have to extend from side to side. This required the addition of beams along the top of the bulkhead as shown in blue in Figure 5.13. These beams make the members along the top of the bulkheads continuous in order to move the loads out to the bottom of the side trusses.

For the two concept designs, three structural floor configurations were considered. The first was an existing product from Baultar Composite Inc. This product is a self-supporting composite floor called the Bee-Lite Floor. The specifications for this floor are found in Appendix A.

The second configuration was a steel sandwich panel. This is similar to the aluminum sandwich panels shown in Figure 5.4(b), however steel is used as the skin material. The third configuration is an aluminum sandwich panel that is the same as shown in Figure 5.4(b).

All of the floor configurations were analysed with the 3.0 g vertical load. The "20 mm core" panel was a steel sandwich panel (with a 20 mm thick core) that was analysed for the first concept design where the longitudinal beams were retained. All other configurations were analysed for the second design concept where there were no longitudinal beams. Therefore, these floor designs required a higher thickness. The Bee-Lite floor deflection was determined from the Baultar specifications in Appendix A.

The displaced shape profile for each of the floor configurations from one side of the bus to the other (at a location half-way along the length of the bus) is shown in Figure 5.14.

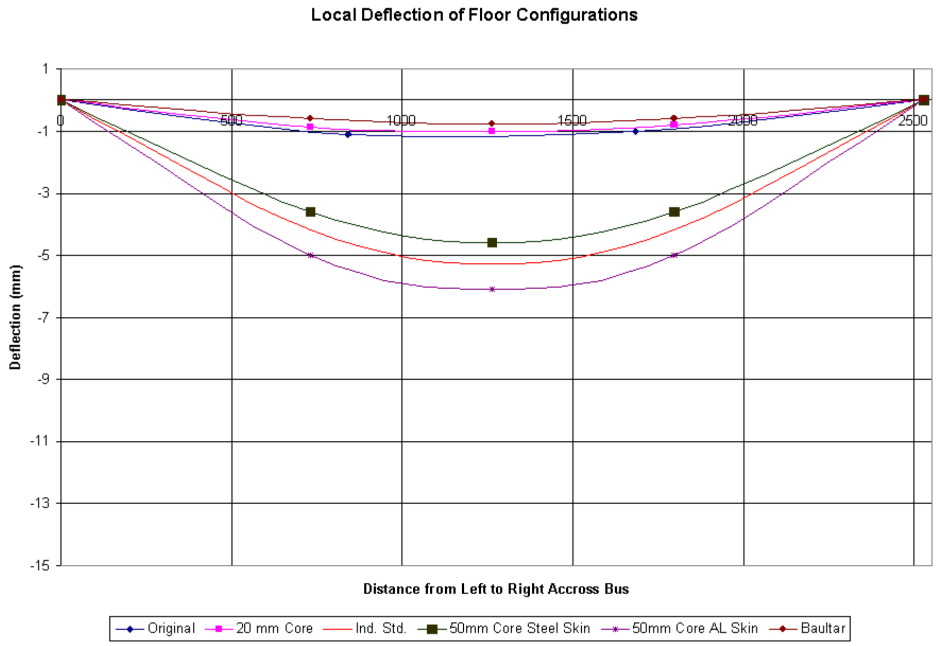


Figure 5.14: Intercity Bus Floor Concept Displacements

From this plot it is seen that the 20 mm floor without the transverse beams provides the same stiffness of the original floor. In this case the longitudinal beams still provide significant support for the structural floor. The Bee-Lite floor, without any lateral or longitudinal beams, also provides the same stiffness; therefore, this floor is very stiff. The other two concepts (50 mm steel and aluminum sandwich panels) are less stiff; however, they are close to the industry standard value of acceptable deflection at approximately 5 mm.

This may still be unacceptably high for an intercity bus floor deflection. Further investigation into the dynamic characteristics of the floor is required before a final assessment of these designs is possible. The industry standard is based upon the North American Transit Industry requirements, as described in Appendix A.

The stresses in all of the design concepts were within the design parameters. The maximum bending stresses at the outer fibre of the steel or aluminum skin for all of the design concepts were 80 MPa and 50 MPa, respectively. These values are all well below the yield values. The core shear stresses are also well below the shear strength of 0.66 MPa (95 PSI) based upon the selected core material called Core-Cell. Its properties are described in Appendix B.

Summary of Results for the Floor Design Concepts

A summary of the results of the analysis of the floor design concepts is provided in Table 5.7.

Table 5.7: Summary of Intercity Bus Floor Concept Designs

CONFIGURATION	WEIGHT SAVED (kg)	WEIGHT SAVED (percent)
Original Design -lateral steel beams -longitudinal steel beams -plywood surface	N/A	N/A
Semi-supported Structural Floor (1) - 20 mm -removed unnecessary lateral beams -removed X-bracing beams -composite steel/foam floor - 1/32" skins	130	18
Unsupported Structural Floor (1) - 25 mm -removed all floor beams -Bee-Lite structural floor	304	41
Unsupported Structural Floor (2) - 50 mm -removed all floor beams -composite steel/foam floor - 1/32" skins	277	37
Unsupported Structural Floor (3) - 50 mm -removed all floor beams -composite alum/foam Floor - 1/16" skins	390	53

From this table it can be seen that sandwich composite floor designs offer a substantial weight savings over the current plywood/steel beam construction. These designs can result in approximately anywhere from a 40 percent to 50 percent savings.

The displacements of the concept designs, with the longitudinal beams retained, match the original floor deflection. The displacements with the longitudinal beams removed are higher but fall near the industry standard. The stresses from the analysis of all of the floor conceptual designs are well within the design limits.

5.3.4 Window Design Concepts

The current window configuration for the XLII bus consists of glass windows. Every second window is hinged for emergency egress purposes. All other windows are glued in place and this adds to the stiffness of the overall structure. A plot of the current FE model of the roof structure showing the widow representation is shown in Figure 5.15. In the FE model, the glued windows are modelled as diagonal beam elements to represent the stiffness of the glass. The hinged windows do not add structurally to the roof, therefore they are not included in the model (as shown by the lack of beams at every second window space).

Transport Canada's current regulations stipulate that every second window is to be hinged (for emergency egress requirements). The intention of this study is not to question that regulation. It is to assess the effect of employing the full stiffness of all the bus windows to determine whether the bus weight can be reduced. If shown to be significant, intercity bus manufacturers and operators can propose alternative methods that satisfy the emergency egress requirements while enabling lighter weight buses.

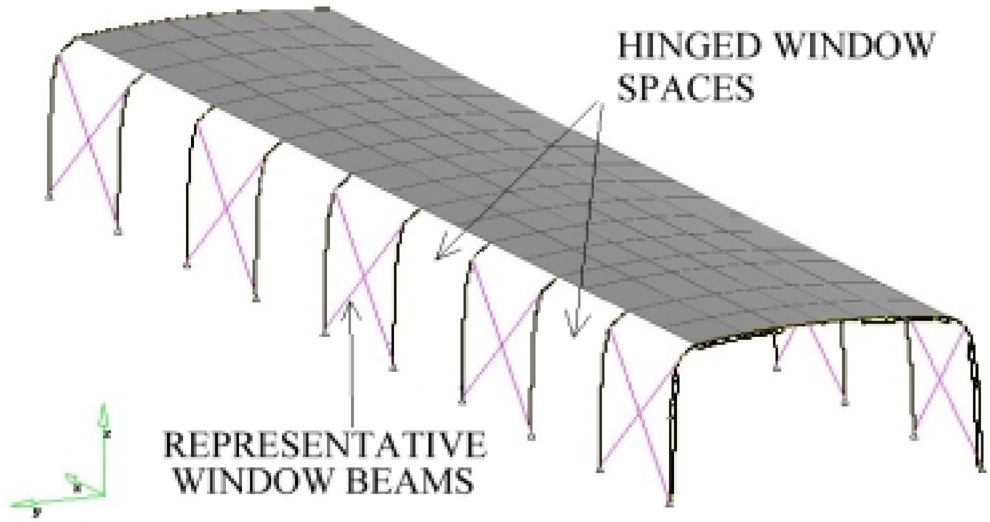


Figure 5.15: Prévost Car XLII Intercity Bus Current Window FE Model Configuration

In this concept design, the effect of gluing all of the windows in place is studied to determine whether the added stiffness will permit any reduction in weight. This is thought to be possible since the added window stiffness will increase the overall moment of inertia of the bus, resulting in reduced stresses that may lead to smaller structural members.

The FE model of the XLII bus with all of the windows considered to be glued in place is shown in Figure 5.16. The window glass for each window space is now modelled using the same diagonal beam elements as used in the glued windows of the original configuration.

The change in stiffness of the bus structural model associated with the addition of the windows is demonstrated in Figure 5.17. This plot presents curves of the deflection along the bottom of the side truss for the original configuration (with every second window fixed in place) and for the configuration where all of the windows are considered fixed in place. A comparison of these results shows that approximately a 5 percent increase in stiffness (maximum) can be achieved as a result of fixing all the windows. A comparison of the stresses in the roof between the two analyses shows approximately a 1 percent decrease in the longitudinal stress component.

The loads used for these analyses were vertical bending loads where the effect of gluing the windows in place did not produce a significant increase in the bending stiffness. Fixing all the windows in place may be more significant for torsional loads. This load case was not analyzed in this study, but should be considered before any final decision is made on the total effect of gluing all of the windows in place.

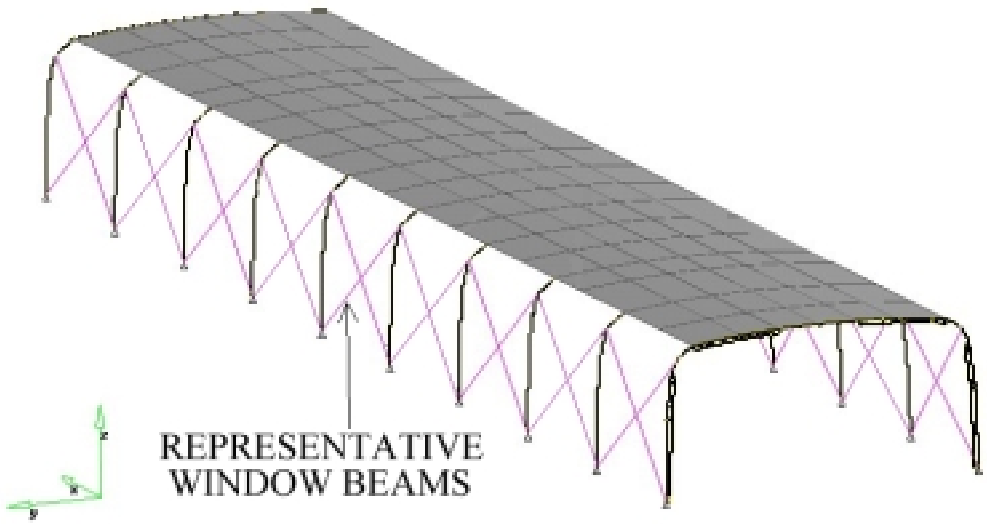


Figure 5.16: Prévost Car XLII Intercity Bus Completely Fixed Window FE Model Configuration

In addition to determining the effect of gluing the windows in the original configurations, the effect of fixing the windows in the new concept design was studied. In this case, the new roof, floor and side truss concept designs were analysed with and without the windows fixed. As shown in Figure 5.17, fixing the windows provides a negligible increase in stiffness over the added stiffness of the new roof, floors and truss.

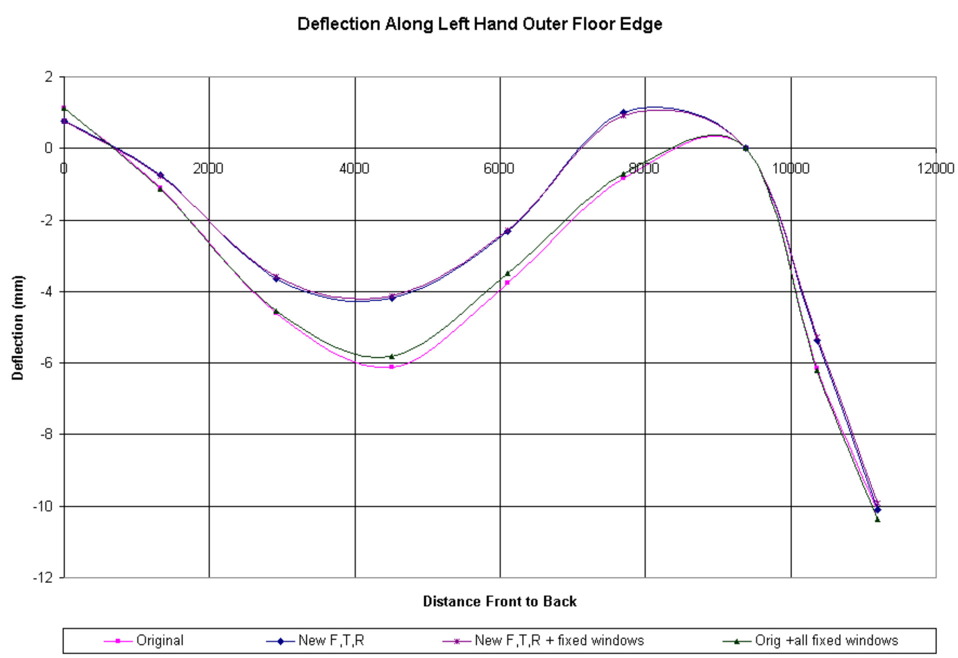


Figure 5.17: Intercity Bus FE Model Floor Deflection for Different Configurations

5.3.5 Combined Component Effects

Up to this point, the work performed on the three individual components (roof, side truss and floor) has focussed on the optimization of each component separately. However, the three components are structurally connected. It is expected that further weight reduction can be achieved by considering the combination of the stiffness of the three components.

The stiffness and the deflection of the bus structure are dependent upon the overall moment of inertia of the structure. In general, structures with larger cross-sectional profiles have larger moments of inertia. For example, a box beam with dimensions of 4x4 units will have a significantly higher moment of inertia then a box beam with dimensions of 2x2 units. Therefore, in the case of the bus structure, if the roof and undercarriage structures are connected to the side truss and floor structure, the overall moment of inertia of the cross-section will increase and the stiffness will increase. Consequently, the deflections will decrease.

A reduction in overall deflections is not required since the new concept designs must only match the original stiffness. Therefore, to offset the reduced deflections from the increase in the overall bus moment of inertia through the combination of individual component stiffnesses, the bus structure can be “softened” through the use of smaller and lighter members in selected areas.

When considering the bus cross-section as an integral section, the effect of including the undercarriage structure as part of this section is studied. This structure consists of the lateral bulkheads and floor of the baggage compartment and the fuel tanks. The addition of this structure can further increase the overall moment of inertia of the bus structure if a longitudinal shear web can be used to transfer the bending load from the baggage compartment/fuel tank floor to the passenger area floor. This may not be practical because of access problems with the baggage. However, this effect was considered to have sufficient potential to pursue further.

Figure 5.18 shows the change in the moment of inertia of the bus from the combination of the individual component stiffness. This is a simplified plot of the bus cross-section that depicts the side trusses, floor, roof, and undercarriage. The baseline for this comparison is the configuration where the floor and side trusses are considered attached to provide a “channel” effect. This configuration has an overall moment of inertia, I.

When the roof is attached to the side trusses and floor, the moment of inertia increases by a factor of 1.5. When the undercarriage structure is included, the moment of inertia is twice the baseline. This is determined through comparison of the displacements at the centre of the bus for each configuration, as shown in Figure 5.19.

Since the overall stiffness of the bus increases when the individual component stiffnesses are combined, further weight reduction is possible if the bus is now considered to be overstiff. However, the roof and floor have local design constraints, so that their structure cannot be reduced in size. Hence, further weight reduction is not possible in these components. However, the side truss weight can be considered for further reduction since the design is based upon the overall bus design loads. Based on this, the top and bottom rails of the side truss were reduced to one-half size with the resulting bus displacement shown in the plots of Figure 5.19. It can be seen that the model with the one-half size top/bottom chord is less stiff, but is still stiffer than the baseline design.

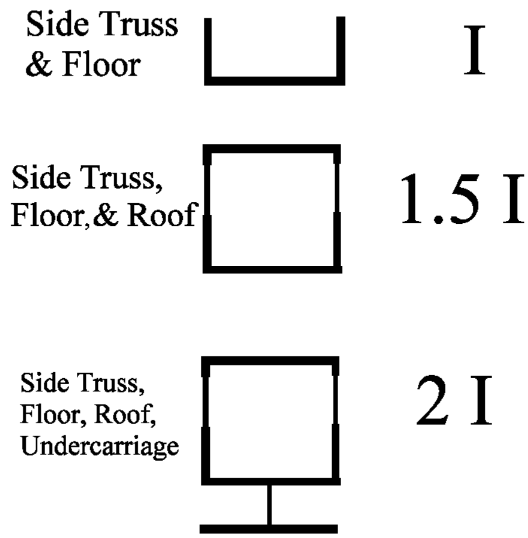


Figure 5.18: Prévost Car XLII Intercity Bus Moment of Inertia Effect of Combined Bus Components

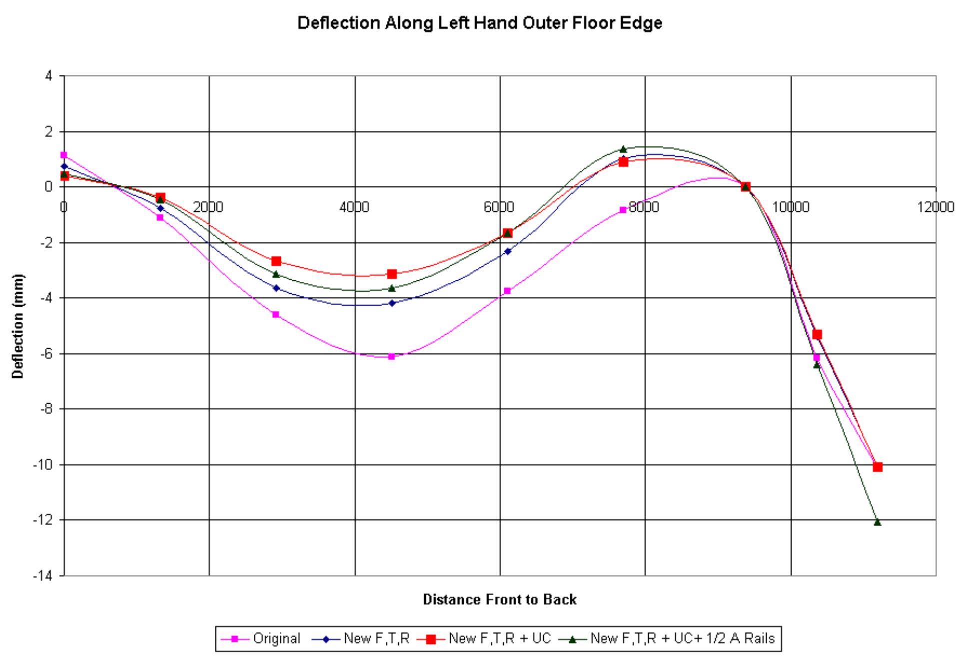


Figure 5.19: Intercity Bus Displacements for FE Model of Combined Bus Component Configurations

To confirm that the structural weight of the truss can be reduced if the components are tied together, the stresses in the members were checked. The results are shown in Table 5.8.

With the undercarriage structure added to the side truss, floor, and roof components the stresses drop significantly in the roof and the floor. When the top/bottom chords of the side truss are reduced to half size, the stresses increase in the roof but remain unchanged elsewhere. Therefore, the reduction in size of the truss top and bottom chord is possible for an additional weight saving of 96 kg.

Table 5.8: Intercity Bus FE Model Stresses from Combined Bus Component Configurations

Configuration	Maximum First Principal Stress (MPa)		
	Floor	Roof	Truss
Truss+floor+roof	62	97	64
Truss+floor+roof+underC	40	36	64
Truss+floor+roof+underC+1/2 size truss rails	40	44	64

In summary, combining the bus structural components provides an increase in moment of inertia that translates into an increase in stiffness. There is also a reduction in stress due to increase in moment of inertia. The reduction in stress permits a reduction in the size of the top and bottom truss chord for an additional weight saving of 96 kg. In addition to this, if the truss exterior web plate was used as the finish panel, further weight reduction is realized.

5.3.6 Total Potential Weight Savings

From the analysis performed on the lightweight concept designs of the roof, floor and side truss, an estimate is generated of the total weight savings possible. This is summarized in Table 5.9 where the maximum weight saved of all of the concept designs is presented. This task shows that a 50 percent weight savings is possible on the intercity bus structural components.

Table 5.9: Overall Intercity Bus Design Concept Weight Savings

Component	Maximum Weight Savings	
	(kg)	(percent)
Roof	330	57
Side truss	188	41
Floor	390	53
Average	N/A	50

These components are 17 percent of the total bus weight. Therefore, an overall intercity bus weight savings of approximately 9 percent is possible by optimizing the bus structure. Further optimization the bus components is expected to produce even greater weight savings. It is estimated that full optimization will generate a weight savings in the order of 20 percent.

6. PREDICTED SAVINGS FROM LIGHTWEIGHT CONCEPTS

6.1 Estimated Intercity Bus Life Cycle Cost Reduction

In order to select the optimum configuration for the roof, side truss, and floor components studies in Section 5, the intercity bus LCC savings associated with these components have to be determined. This allows the identification of the components that offer the best potential for further development. The costs considered include material, fabrication and operating costs.

As described in Section 3, the costs associated with the operation of intercity buses were gathered from several sources. All of this information was based on overall bus operating costs with virtually no information directly related to cost savings per weight savings. Therefore, it is difficult to accurately determine the complete LCC savings from lighter intercity buses. An estimate is supplied based upon the material available. It should be interpreted as a rough order of magnitude approximation.

The costs of materials and fabrication of the current XLII structural components have been supplied by Prévost Car. Metal fabricators and suppliers were contacted with limited success to determine the fabrication costs of the new concept designs. Cost estimates were not available since detailed information was required on the fabrication processes of the concept designs.

As demonstrated in Section 5.3.6, the estimated weight savings for an intercity bus utilizing the new design concepts is 9 percent of the total bus weight. It is also estimated that an overall 20 percent weight savings is possible through a total bus optimization. Therefore, the estimated LCC savings presented in the following sections are for a 9 percent and 20 percent weight savings.

6.1.1 Fuel Savings

Based upon the estimated LCC of intercity buses provided in Section 3, the complete intercity bus industry in Canada spends approximately $70M on fuel per year for 375 million km travelled. From Reference 7, it is known that a 10 percent reduction in the weight of urban buses translates into approximately a 5 percent fuel savings. It is assumed that the savings for intercity buses are of the same order. Therefore, with a 9 percent reduction in the weight of an intercity bus, a 4.5 percent fuel saving is realized. This produces a $3.2M ($70M * 0.045) savings in fuel per year. With an average bus life of 15 years, the total LCC fuel saving is expected to be $47.3M (excluding inflation). For a 20 percent weight reduction, the total LCC saving is estimated at $105M.

6.1.2 Maintenance Savings

Information provided in Reference 6 estimates that maintenance costs for urban buses account for approximately 10 percent of operating expenses, and that this is approximately equal to the fuel costs. Therefore, the LCC maintenance saving for urban buses associated with a 9 percent and 20 percent weight reduction is expected to be $47.3M and $105M, respectively, over a 15-year life.

The maintenance costs (mostly brakes and tires) for intercity buses are not expected to be as severe as for urban (transit) buses. Conservative estimates from Transport Canada personnel rate intercity bus maintenance costs at approximately 50 percent of urban bus costs. Therefore, the estimated (15-year) maintenance costs of intercity buses for a 9 percent and 20 percent weight savings are $23.7M and $52.5M, respectively.

6.1.3 Road Infrastructure Damage Savings

From Reference [7], it is estimated that reducing the weight of an urban bus by 10 percent results in a saving on road infrastructure damage of $0.012 per bus kilometre. From Section 3 the total annual mileage of intercity buses in Canada is estimated at approximately 375M kilometres. Similar to the argument in Section 6.1.2, it is estimated that the infrastructure damage from intercity buses is approximately 50 percent of the damage from urban buses. This is due to a three-axle intercity bus configuration versus a two-axle configuration for transit buses. The intercity buses also travel at higher speeds on roads developed for heavy vehicles. Therefore, the estimated LCC cost savings (15 years) for a 9 percent and 20 percent weight reduction for road infrastructure damage are $2.1M and $4.5M, respectively.

6.1.4 Pollutant Emissions Cost Savings

From Reference [7], it is estimated that a 10 percent urban bus weight reduction translates into a saving on pollutant emissions of $0.0108 per bus kilometre. These costs are based upon costs of measures that have to be put in place to eliminate, mitigate or reduce the quantity of pollutants released. It is assumed that this is equally true for intercity buses.

Based upon the total annual mileage of intercity buses in Canada at approximately 375 million kilometres, the LCC savings (15 years) for a 9 percent and 20 percent weight reduction for pollutant emissions are $54.7M and $121.5M, respectively.

6.1.5 LCC Increases

During this study, the components that were chosen to determine their weight savings potential were analyzed for several configurations that included different materials. The intercity bus original configuration is mostly steel (except for the roof, which is partly aluminum) with proposed changes being an all-aluminum configuration, or composite panels. Therefore, changing to other materials would have an effect on the cost of production of these components.

In Reference [8], a comparison of production costs of bus models that used different materials was carried out. It was found that the production cost variance in going from an all-steel configuration to composite panels is approximately 1 percent. Consequently, the manufacturing cost changes of the proposed composite design concepts are considered negligible.

Also, from discussions with manufacturers, it was found that material and fabrication costs of aluminum are approximately twice that of steel. Of the components studied, only one was changed from an all-steel configuration to an all-aluminum configuration. This was the side truss. A calculation of the cost change if this component was fabricated completely from aluminum at twice the cost of steel showed that the increased cost is less than 1 percent of the bus manufacturing costs.

Therefore, the total increase in fabrication cost for any of the proposed design concepts is considered small. With improved fabrication methods and selected procedures to reduce the cost of working with lightweight materials, it is estimated that fabrication costs for any of the proposed concept designs will be maintained at or near current costs.

6.1.6 Summary of LCC Savings

The LCC savings resulting from reducing the weight of an intercity bus by 9 percent and 20 percent are summarized in Table 6.1. This reflects the total intercity bus industry savings in Canada based upon the present bus population. As shown, the overall cost savings associated with a 9 percent decrease in intercity bus weight over a 15-year period is estimated at $127.8M. If a 20 percent weight reduction could be achieved, the total LCC savings would be approximately $283.5M. The estimated operator costs savings will be slightly higher than the societal cost savings, accounting for 56 percent of the total savings.

Table 6.1: Intercity Bus Life Cycle Cost (15 years) Variance due to a 9 Percent and 20 Percent Weight Reduction

Life Cycle Cost Component	**Cost Variance ($M)**	
	9 Percent Savings	20 Percent Savings
Operator:		
Fuel	-47.3	-105.0
Maintenance	-23.7	-52.5
Societal:		
Road Infrastructure	-2.1	-4.5
Pollutant Emissions	-54.7	-121.5
Fabrication	0.0	0.0
Total	**$-127.8M**	**$-283.5M**

6.2 GHG Emissions Reduction

With the high fuel savings, a significant reduction in GHG emissions will also result. For every litre of fuel consumed approximately 2.7 kg of CO_2 is produced. From the Reference [5] data, an intercity bus uses an average of 39 L/100 km. Based upon the total annual mileage of intercity buses in Canada of approximately 375 million kilometres, the total fuel used by the intercity bus fleet per year is 146 million L. Based on Reference [2], a 9 percent weight reduction results in a 4.5 percent fuel saving. Therefore, a 9 percent bus weight reduction translates into a reduction of approximately 17.7 million kg (17.7 Ktonne) of CO_2 per year. Over the life of the fleet (15 years), the total reduction in CO_2 is 266 million kg (266 Ktonne). A 20 percent intercity bus weight reduction will reduce GHG emissions by 591 million kg (591 Ktonne) over the life of the fleet.

6.3 Axle Weight Reduction

As identified in Section 1, the axle weights of intercity buses are regularly over the memorandum of understanding (MOU) limits [2] established between the Canadian provinces. The limits for the three axle weights of intercity buses are shown in Table 6.2.

Assuming that current intercity buses have axle weights at the MOU limits, and based upon the weight saved from the proposed structural concept designs, a 9 percent reduction in weight will reduce the front axle weight to 6,788 kg. Assuming an overall uniform 20 percent reduction in the weight of the bus, then the axle weight would reduce to 6,224 kg. This is well below the MOU limit, and provides a significant margin of safety (see Table 6.2). [Note: The estimated axle weight savings are based upon the GVWR of the bus minus the weight of passengers, fuel, and luggage (i.e. curb weight). These components weigh 15,810 kg and are considered constant.]

The MOU rear (drive) and tag axle limits are 9,100 kg and 6,000 kg, respectively. Similar to the above prediction for the front axle, a 9 percent and 20 percent reduction in the weight of the bus would decrease the drive and tag axle weights (assuming the bus axle weights are at the MOU limit) to those as specified in Table 6.2.

Table 6.2: Intercity Bus Potential Axle Weight Reduction

Axle Location	Current Weight (kg)	Potential Weight Reduction			
		9 Percent		20 Percent	
		Wt saved (kg)	Weight (kg)	Wt saved (kg)	Weight (kg)
Front	7,250*	462	6,788	1,026	6,224
Drive	9,100*	579	8,521	1,287	7,813
Tag	6,000*	382	5,618	849	5,151

*Assumes the weight is the same as the MOU limit.

6.4 Manufacturing Considerations

It is estimated that new generation buses that employ these lightweight composite designs will be no more expensive to manufacture than current intercity buses. However, operators will enjoy significantly reduced operating expenses. Therefore, Canadian manufacturers who use these lightweight concepts can potentially increase their market share both in Canada and in the United States.

7. SELECTION OF DESIGN CONCEPTS

The selection of the optimal design concepts for each of the studied components is presented in this section. This selection process was based upon the determination of the greatest life cycle costs (LCC) savings for each of these design concepts. As detailed in the previous section, data on the potential LCC savings for lightweight intercity buses was gathered for the fuel, maintenance, infrastructure damage and pollutant emissions. These are all quantified and are based directly upon LCC savings per weight saved [Note: these LCCs are identified as LCC-weight in this section]. However, other LCCs considered important in all of the design concepts could not be quantified within the scope of this phase of the project. These are: collision damage, fatigue and corrosion susceptibility.

In order to identify the optimal design concepts, a methodology was devised to compare the LCC savings for each concept based upon the quantifiable (LCC-weight) and unquantified "other" LCCs. The procedure is to determine a set of "weightings" for each LCC and a set of "weightings" for each design concept. These weightings are then multiplied to determine a "Weighted Life Cycle Cost Factor" for each individual LCC of each concept design. The weighted LCC factors of the design concepts are then summed and compared, with the lowest factor offering the highest potential for LCC savings. The results of this comparison are shown in Table 7.1. A discussion of the selection process for the "weightings" and the optimal design concepts is provided below.

In general, the numbers chosen for the weightings are subjective. While not generated directly from "hard numbers" on fatigue, collision or corrosion data, the relative importance of one weighting to another is considered valid. This is sufficiently accurate to provide a valid comparison of the concept designs for LCC savings.

The first set of weightings rates the importance of each of the LCC (Fatigue, Collision, Corrosion and LCC-weight) for each of the components (floor, side truss and roof). These weightings are found in the row entitled "Cost Factor Weighting". The higher the importance of the LCC for this component, the higher the weighting is. As shown in the last column of the "Cost Factor Weighting" row, the addition of these factors always sum to a value of 100. As will be discussed later in this section, the value of 100 is used to represent the Overall Rating of a current bus (i.e. the baseline). This provides a benchmark for comparison of the concept designs for each component.

The selection of the weightings for each LCC is based upon the relative importance of each LCC for that particular component. For example, Corrosion Susceptibility is considered very low in the roof and side truss. These components are protected from corrosive elements. Therefore, they are given a weighting of 5 (i.e. 5 out of 100). Conversely, corrosion susceptibility is considered to be much higher in the floor due to passenger generated corrosive elements such as salt from footwear. Consequently, it is given a weighting of 30.

Fatigue susceptibility is considered to be very low in the floor and roof (weightings of 2.5) since cyclic loading is not predominant in these components. The weighting is higher for the side truss (weighting of 10) due to the consideration of the cyclic bending loads carried by the truss during operation.

Table 7.1: Intercity Bus Optimal Lightweight Design Concepts

Optimal Floor Configuration

Design Concept	Weight (Kg)	Weight Savings (Kg)	LCC Savings ($M)	Weighted Life Cycle Cost Factors: Fatigue Sus. W	Fatigue Sus. Factor	Collision Sus. W	Collision Sus. Factor	Corrosion Sus. W	Corrosion Sus. Factor	LCC-weight Factor	Overall Rating
Cost Factor Weighting					**2.5**		**7.5**		**30**	**60**	**100**
Baseline - steel frame/plywood	740			1.0	2.5	1.0	7.5	1.0	30.0	60.0	100.0
Semi-supported structural floor 20mm core steel sandwich panel	610	130	$4.09	1.0	2.5	1.0	7.5	1.3	37.5	49.5	97.0
Unsupported Baultar structural floor	436	304	$9.56	1.0	2.5	1.0	7.5	1.3	37.5	35.4	82.9
Unsupported structural floor 50mm core steel sandwich panel	463	277	$8.71	1.0	2.5	1.0	7.5	1.3	37.5	37.5	85.0
Unsupported structural floor 50mm core Al sandwich panel	350	390	$12.26	1.0	2.5	1.0	7.5	1.5	45.0	28.4	83.4

Optimal Side Truss Configuration

Design Concept	Weight (Kg)	Weight Savings (Kg)	LCC Savings ($M)	Weighted Life Cycle Cost Factors: Fatigue Sus. W	Fatigue Sus. Factor	Collision Sus. W	Collision Sus. Factor	Corrosion Sus. W	Corrosion Sus. Factor	LCC-weight Factor	Overall Rating
Cost Factor Weighting					**10**		**10**		**5**	**75**	**100**
Baseline - HSS steel	462.4			1.0	10.0	1.0	10.0	1.0	5.0	75.0	100.0
Diagonals replaced with steel sandwich panels	413.4	49	$1.54	1.0	10.0	1.0	10.0	1.5	7.5	67.1	94.6
All aluminum truss	370.3	92.1	$2.90	1.0	10.0	1.0	10.0	1.5	7.5	60.1	87.6
Aluminum rails with aluminum sandwich panels	285.3	177.1	$5.57	1.0	10.0	1.0	10.0	1.5	7.5	46.3	73.8
Aluminum rails with composite panels	283.3	179.1	$5.63	1.0	10.0	1.5	15.0	1.0	5.0	46.0	76.0
Steel rails with composite panels	375.4	87	$2.74	1.0	10.0	1.5	15.0	0.5	2.5	60.9	88.4
Composite rails with composite panels	274.3	188.1	$5.92	1.0	10.0	2.0	20.0	0.0	0.0	44.5	74.5

Optimal Roof Configuration

Design Concept	Weight (Kg)	Weight Savings (Kg)	LCC Savings ($M)	Weighted Life Cycle Cost Factors: Fatigue Sus. W	Fatigue Sus. Factor	Collision Sus. W	Collision Sus. Factor	Corrosion Sus. W	Corrosion Sus. Factor	LCC-weight Factor	Overall Rating
Cost Factor Weighting					**2.5**		**25**		**5**	**67.5**	**100**
Baseline - SS ribs /aluminum skin	584			1.0	2.5	1.0	25.0	1.0	5.0	67.5	100.0
Aluminum ribs/aluminum skin	290	294	$9.25	1.0	2.5	1.0	25.0	1.5	7.5	33.5	68.5
Aluminum Ribs with fiber glass sandwich panels	254	330	$10.38	1.0	2.5	1.5	37.5	1.5	7.5	29.4	76.9
Aluminum ribs with aluminum sandwich panels	254	330	$10.38	1.0	2.5	1.0	25.0	1.5	7.5	29.4	64.4

Collision susceptibility is considered to be relatively low in the floor and side truss with weightings of 7.5 and 10, respectively. It is considered to be important in the roof due to the requirement for the roof to maintain an intact passenger compartment during rollover. Therefore, it is given a weighting of 25.

The second set of weightings rates the performance of each design concept with respect to each unquantified LCC (i.e. fatigue/collision/corrosion susceptibility). These weightings are all found in the "W" columns in Table 7.1.

As shown in the floor concept designs for corrosion susceptibility, weightings of 1.0, 1.3 and 1.5 are used for the baseline, all three steel sandwich panels and the aluminum sandwich panel, respectively. The higher the weighting, the more prone the design is to corrosion. From these numbers, it is predicted that the steel sandwich panels will be more prone to corrosion (1.3 times more prone) than the original plywood/steel configuration and the aluminum sandwich panel is considered to be more prone (1.5/1.3 = 1.2 times more prone) to corrosion than the steel sandwich panel.

For collision susceptibility, aluminum and steel were considered to be very similar (weighting of 1.0) while composites were considered to be more prone to damage from collision. Consequently, concept designs that utilize composites have a higher weighting for collision susceptibility. Hybrid metal/composite panels are given a weighting of 1.5. All composite panel designs are given a weighting of 2.

For fatigue susceptibility, all concept designs are considered similar in ability to withstand damage from fatigue. Therefore, all fatigue susceptibility weightings are set to 1.0. Consequently, fatigue susceptibility is not a consideration in the selection of the optimal design concepts.

In order to determine the optimum designs, weighted LCC factors are generated for each concept design. These are found in the "factor" columns in Table 7.1. For the unquantified fatigue/collision/corrosion LCC, the two sets of weightings are multiplied to generate the weighted LCC factors. For example, the weighted corrosion susceptibility LCC factor of 7.5 for the "all aluminum truss" side truss concept is calculated by multiplying the "cost factor weighting" of 5 by the design concept "W" weighting of 1.5.

The weighted factors for the quantified savings (LCC-weight) are not generated using this method. These factors are calculated directly from the ratio of the weight of the new concept design to the weight of the baseline multiplied by the "cost factor weighting". For example, the weighted LCC-weight factor of 60.1 for the "all aluminum truss" side truss concept is calculated by (370.3 kg/462.4 kg*75), where 75 is the cost factor weighting. In general, if a concept design has a 40 percent weight savings then the factor will be twice as low (from the baseline) than for a design with a 20 percent weight savings.

The weighted factors for LCC-weight are considered to be the most important because of the potential for high LCC reduction through weight reduction. Except for the weighted factors generated for the floor concept designs for corrosion susceptibility, the weighted factors for LCC-weight are much higher than any other factor.

All of the weighted LCC factors for each design concept are summed to determine an "Overall Rating" as seen in the last column of the table. As discussed earlier in this section, the overall rating for the baseline of each component is given a value of 100. This is set as the basis for comparison for all of the design concepts. If a design concept has an overall rating over 100, it offers no LCC savings over the current design. The design concept with the lowest overall rating offers the most potential for LCC savings.

For example, in the side truss component, the weighted factors for the "aluminum rails with aluminum sandwich panels" are 10, 10, 7.5, and 46.3, for fatigue, collision, corrosion and LCC weight, respectively. These total to an overall rating of 73.8 (as shown in the last column). From a review of overall rating of each of the design concepts for the side truss, it is seen that this design has the lowest rating. Therefore, it is considered the optimal side truss concept design.

From a review of the overall rating of each design concept for each component, it is seen that sandwich panel designs offer the best potential for LCC savings. The weighted LCC factors show that aluminum sandwich panels offer a slight advantage over fibreglass sandwich panels. However, given the subjective nature of the selection of the weightings, fibreglass sandwich panels can also be considered to offer high potential for LCC savings in lightweight intercity bus designs.

Finally, it can be seen in the overall rating of each design concept that all of the concept designs have a rating less than the baseline (i.e. 100). This indicates that all of the new design concepts offer a potential for LCC savings.

8. PHASE 2 PROGRAM DEFINITION

The second phase of the intercity bus weight reduction program will focus on the validation, detailed design and testing of the design concepts produced from the Phase 1 work.

In Phase 1, three bus structural components were investigated for potential weight reduction: the roof, the side truss and the floor. Many design concepts were studied and recommendations were provided for the most promising concepts for each of the three structural components based upon LCC reduction.

In Phase 2, the preferred design concepts will be selected for each of the three bus structural components, and a review of the current intercity bus assembly/manufacturing processes will be carried out to determine the ease of transition to manufacturing the new concept designs.

The next step will be the structural validation and detailed design of the concepts. This will be carried out by first developing and testing sample coupons of the proposed structural configurations to confirm the integrity of the designs. The attachment details of the individual components (for example, roof to side truss) will then be investigated through the fabrication and testing of experimental models of the connection points of the separate components. From the results, the detailed design of the preferred concepts will be carried out.

The last step will be the validation of the design concepts in terms of manufacturability. A full-scale longitudinal section of the bus will be fabricated using the preferred design concepts of the roof, side truss and floor. All of the connection/assembly details will be determined and finalized to provide proof of concept viability.

In Phase 2, the following tasks will be performed:

Task 1: Review Phase 1 results and select two design concepts for each component

Task 2: Review intercity bus manufacturing/assembly procedures

Task 3: Develop and test coupons of structural configurations

- Design test coupons of structural sections
- Develop test procedure for testing coupons
- Test coupons for structural integrity against design criteria

Task 4: Detailed design of individual and assembled design concepts

- Develop experimental test specimens of component connection details
- Test connection detail specimens against design criteria

Task 5: Full-scale manufacturing of components for proof of concept

- Manufacture full-scale mock-up of roof/floor/truss section
- Validate assembly/manufacturability of mock-up

9. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study, the development of practical lightweight structural components for intercity buses is feasible. The redesign of three main structural components (i.e. roof, side truss and floor) resulted in an overall bus weight reduction of 9 percent. It is expected that if all of the intercity bus components were optimized, a total weight reduction of 20 percent could be realized.

It was found that fixing all of the windows in place does not significantly increase the vertical bending moment of inertia of the bus structure. However, torsional load must be considered before determining the total benefit of fixing all of the windows.

It is concluded that the total LCC savings of the entire Canadian fleet of intercity buses from the 9 percent weight reduction is in the order of $127.8M. It is further estimated that a 20 percent reduction in the weight of an intercity bus would translate into LCC savings of $283.5M for the entire Canadian fleet. The operator LCC savings (fuel and maintenance) account for 56 percent of this, while the societal (road infrastructure damage and pollutant emissions damage) account for 44 percent.

Decreasing the weight of intercity buses by 9 percent would also significantly decrease instances of axle weights exceeding the inter-provincial MOU limits. A 20 percent weight reduction will virtually eliminate exceedances.

It is concluded that a reduction in the weight of intercity buses will have a significant impact on fuel savings. It is estimated that a 9 percent weight reduction will save $47.3M in fuel costs and a 20 percent weight reduction will save $105M over the life of the Canadian intercity bus fleet.

Lightweight intercity buses will have a significant positive effect on air pollutant reduction. A 9 percent bus weight reduction will reduce CO_2 production by approximately 266M kg (266 Ktonne) litres over the life of the Canadian fleet. Considering CO_2 and the other pollutants, this translates into LCC savings of $54.7M. A 20 percent bus weight reduction would reduce CO_2 production by approximately 591M kg (591 Ktonne) or $121.5M in terms of LCC savings.

Lightweight intercity buses will also reduce the infrastructure damage now produced by heavy buses. It is estimated that a 9 percent weight will save $2.1M in infrastructure costs over a 15-year period. A 20 percent weight reduction would save $4.5M over the same period. This is directly as a result of a reduction in the front, drive and tag axle weights.

A cursory look at the effect of incorporating seat belts into intercity buses showed that this feature will probably add to the weight of the bus because of the increased strength requirements and attached hardware. Manufacturers are reluctant to tackle this issue until regulations requiring the use of seat belts are imposed. These regulations may be forthcoming, therefore, for future bus designs, strong consideration should be given to the design of the floor to accept seat belt anchoring requirements.

In conclusion, it is highly recommended that the bus weight reduction program outlined in Section 8 of this report be carried out, with the ultimate goal of reducing the weight of intercity buses by 20 percent. This will give Canadian intercity bus manufacturers a competitive edge in the North American bus market while reducing infrastructure damage and CO_2 emissions in order to meet the Kyoto Protocol targets. The cost of the study is dwarfed by the $283.5M expected to be realized in cost savings to Canada taxpayers and bus operators.

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APPENDIX A:

BAULTAR FLOOR SPECIFICATIONS

BAULTAR COMPOSITE	TECHNICAL SPECIFICATION "ABRASTOP™/BEE-LITE™" STRUCTURAL FLOORING

ADVANTAGES

Abrastop™ is a tried and tested product. It benefits from over 12 years of service in Montreal's Métro system (rubber tire Transit Cars); over 7 years of use in the Vancouver, BC "Skytrain" (LIM- Steel wheel); in other North American Mass Transit system cars in NYCT (New York), PATH (New Jersey), STC (Mexico) and TTC (Toronto). By incorporating this proven product into an advanced design structural floor; Abrastop™/BEE-LITE™ defines the standards to meet in regards to:

MAINTENANCE

- **Ease of cleaning** (chewing gum, marks and graffiti are easily removed);
- **Resistance to rot.** The BEE-LITE™ panel core was specially designed to solve this problem. Furthermore the ABRASTOP™ floor covering, installed over the BEE-LITE™ panel, acts as a protective barrier against water and liquid infiltration (cleaning soaps, solvents, alkaline etc.) through the seams, thereby reducing the likelihood of rot & rust wicking out to the car structure & side walls;
- **Maintenance costs are reduced** due to less down time for cleaning & maintenance which can result in a more predictable revenue stream;
- **Installation costs** are reduced when refurbishing or when building new cars.

SAFETY

- ABRASTOP™/BEE-LITE™ structural flooring outperforms all existing Transit requirements (passenger safety) as **to fire, smoke & toxicity** combined ;
- **Non-skid performance** (Passenger safety) is maintained throughout the entire life span of the floor.

AESTHETIC

- Its clean granite-like surface appearance lasts for the useful service life of the car and appeals to passengers. As well, minor local repairs, using the ABRASTOP™ repair kit, are quickly done and blend well into the general floor appearance;
- ABRASTOP™ can be produced with **integrated decorative logos** for car aesthetics.

PERFORMANCE

- **Wear resistance** for the entire useful life of the car, due to the fact that flooring surface may be regenerated "*in situ*". As well, the ABRASTOP™ floor covering resists indentations caused by high heeled shoes;

- The spring effect (spring constant) of the Panel System, in addition to the superior clamping results of the installed Panels all contribute to the structural integrity of the Car;

- The full mechanical liaisons of the Panel System's components, in addition to the adhesives used, provide a guarantee against Panel delamination, thus retaining superior structural integrity, even in the event of a fire.

The Full Life Cycle expectations for the ABRASTOP™/BEE-LITE™ Floor System, the low cost of maintenance and lack of need for repairs, all combine to make this the most economical flooring product - by far!

SYSTEM PROPERTIES

A. GENERAL DESCRIPTION

The ABRASTOP™/BEE-LITE™ system is a composite sandwich panel composed of two main elements :

- ABRASTOP™, an anti-slip (wet or dry) floor covering, easy to clean with a "granite-like" finish is available in a wide range of colours. It offers greater performances due to its unique concept:
  - Use of flexible thermoset resins;
  - Use of wear resistant quartz & silica aggregates;
  - Use of bi-directional reinforcement fibreglass to assure to provide high flexural strength of the panel.
- BEE-LITE™, is a composite core , used in a "sandwich type panel" and is composed of the following elements :
  - Lightweight composite core is designed in the shape of hexapyramidal alternating cells;
  - Composite peripheral profiles used to anchor the panel to the car structure;
  - Resilient syntactic foam reinforced with fibre;
  - A Stainless Steel bottom skin.

The Stainless steel bottom skin is mechanically linked to the core and the profiles using rivets and the elements are glued together with a flexible adhesive; thus obtaining a rigid and integral panel.

Other characteristics:

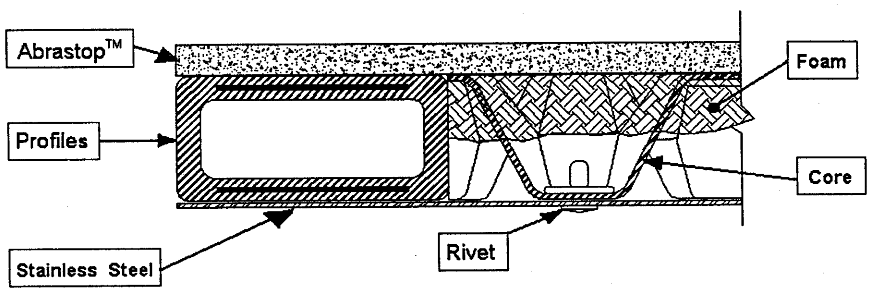
- Designed to withstand high temperatures (even on a localised section of the panel);
- High impact resistance;
- The adhesion between the BEE-LITE™ core and the ABRASTOP™ floor covering is assured using syntactic foam formula, which perfectly unites the core to the floor covering (100% surface of contact). This foam formula has the advantage of being composed of the same resins used in the floor covering and in the core. The homogeneity of the elements used throughout the entire thickness of the panel perfectly bonds them together.

The foam helps to give the floor system a very high resistance to compression and to impact.

A. GENERAL DESCRIPTION (continued)

This mass transit floor system constitutes a rigid and reliable panel, which meets the highest standards regarding safety, longevity and physical, mechanical and environmental performances.

ABRASTOP™/BEE-LITE™ Mass transit Floor System



B. PHYSICAL PROPERTIES	
Standard Dimensions	Thickness: 23.4 ± 1.0 mm (0.921" ± 0.039") Width: ≤ 1524.0 mm (≤ 60") Length: ≤ 3048.0 mm (≤ 120")
Colour (s) available	• Available in a wide range of tones composed by blending our standard colours of aggregates: black, white, blue, green, grey, tan, red and "sand". • Coloration is throughout the ABRASTOP™ thickness. • Very good chromatic stability (Lot shade reference samples are available on request).
Weight	27.0 ± 1.0 kg/m² (5.53 ± 0.2 lb/pi²) *Note: Weight varies depending on panel size and construction.*
Hardness ASTM D-2583	• An average superior to 50 Barcol maintained in production *The hardness of the surface allows this floor covering to resist to the impact of objects that could damage the surface, complicate the cleaning and cause liquid infiltration.*
Dimensional Stability DIN 51962	• ≤ 0.09% length and width wise

C. MECANICAL PROPERTIES	
Deflection	Panels exceed the *North American Transit Industry* requirements and those of the *Sistema de Transporte Colectivo de México* : • Test results against the industry requirement of L/160 represent deflection of 4.1875 mm @ 700 kg/m^2 (1 lb/in^2) • Results obtained of L/1100, represent deflection of 0.609 mm @ 730 kg/m^2 "L" is defined as the shortest distance between structural supports. *Note: Different results can be provided, depending on BEE-LITE™ system design (built to client requirements: size, reinforcements, etc.).*
Compression	The Panels greatly surpass Transit Industry and *Sistema de Transporte Colectivo de México* requirements of 1 lb./in^2. Actual results with Core Tests exceed the specified requirement, by a factor of 600 (4.12 Mpa, 598 PSI) for a panel without foam reinforcements and by a factor of 10000 (69.45 Mpa, 10072 PSI) with high compression foam reinforcements.
Localised Compression ASTM D-695	The minimum localised compression, which is caused by High Heeled Shoes, is 1500 psi (10.34 Mpa). The Panel is designed to surpass it's own Core compression performance owing to the unique contribution of the Abrastop™ Floor Covering, which resists more than 142.88 Mpa (20720 PSI).
Anchoring	When the ABRASTOP™/BEE-LITE™ Panel is fixed to the car structure, it provides a spring effect (spring constant) in order to absorb deflection while maintaining a durable clamping force, without transmitting an overload to the rivets. The following factors contribute : • The adhesive, recommended by Baultar Composite Inc., to bond the Panel to the car structural beams, avoids the "Lubricant Effect" normally contributed by the "Anti-Squeak" Elastomeric tape. Clamping results obtained are increased by the use of adhesives between panels and beams; • Strong and spring like "Daisy-Grip" rivets are used to mount the Panel to the beams (after the panel has been levelled & the adhesive bed has cured).

C. MECANICAL PROPERTIES (continued)	
Shear	The Panels are designed to cope and to absorb shear stresses caused by torsion of the Car Frame, using the Panel components' features to counteract or absorb: • The flexible nature of the Abrastop™ epoxy matrix and the integral nature of it's fibreglass underlay provide a strong, flexible floor covering; • The flexible adhesive, used to bond the panel system, absorbs movement; • The Composite Core also contributes, through its flexibility.
Fatigue	Compression, Flexion and Shear stresses occur in multi-million cycles, over the Transit Car's useful life. The structural integrity of the ABRASTOP™/BEE-LITE™ system, combined with the "spring" effect and superior clamping results, provide the best solution against fatigue related problems.
Structural integrity	The bottom panel skin is riveted to the Core and to the Perimeter Profiles, in order to maintain a mechanical liaison, in addition to the adhesive bond, avoiding the possibility of delamination of the components. Rivets are installed uniformly on the bottom panel skins, with a higher concentration of rivets at the Profiles to avoid stress concentration.
Wear Resistance	The best criterion to measure the wear of the ABRASTOP™ is surely to assess the wear in previously installed systems, in use worldwide. After 10 years of service in the Montreal Métro, we have observed an average wear of 0.0015 in/year. Thus in normal service, the floor is designed to have a useful life much superior to 20 years.
Dynamic Thermal Differential Testing (Localised Heat; sun exposure simulation)	> 100 °C (212 °F)

D. CHEMICALS AND ENVIRONEMENTALS PROPERTIES

Resistance to rot	The Panels are made with materials, which meet the Transit Car's life span, while retaining structural properties, even under extremely humid conditions. Unlike most adhesives, the adhesives used by Baultar Composite Inc. were chosen due to their inherent waterproofing features, as well as for reasons of elasticity and superior ability to bond.
Operating Temperatures	The ABRASTOP™/BEE-LITE™ system easily withstands operating temperatures between –40°C and +45°C (-40°F and +113°F).
Resistance to stains ASTM D-1308	Results obtained after 24 hours of exposure: **PRODUCT** — **RESULT** Methyl Alcohol — Not affected Vinegar 3% — Not affected HCl 30% — Not affected NaOH 10% — Not affected Detergent — Not affected Vegetable oil — Not affected H_2SO_4 30% — Not affected Engine oil 10W-30 — Not affected Mustard — Slight Yellowing Coffee — Not affected *These excellent results are due to the non-porous surface of Abrastop™.*
Resistance to Exposure of Glowing Cigarettes DIN 51961	• Visible stain (on some colours of ABRASTOP™) not removed with Methyl Alcohol but can be erased with the Baultar solvent. • These results are better than all traditional rubber flooring used in the mass transit industry, to date.
Light Fastness ASTM G26	Results obtained after 100 hours exposure to light indicate a light fastness resistance coefficient range from considerable (2) to slight (4) depending on the colour, which is better than most of the other types of rubber coverings tested.

E. SAFETY

Anti-Skid

Test	Finish	Conditions of Test	Dynamic Coefficient of Friction (high speed)
ASTM E-303	Sand Blast	Rubber Dry	> 0.54
	Sand Blast	Rubber Wet	> 0.38

Test	Finish	Conditions of Test	Coefficient of Friction
ASTM D-2394	Sand Blast	Leather Dry (static)	> 0.27
	Sand Blast	Leather Dry (dynamic)	> 0.21
	Sand Blast	Leather Wet (static)	> 0.42
	Sand Blast	Leather Wet (dynamic)	> 0.33
	Sand Blast	Rubber Dry (static)	> 0.42
	Sand Blast	Rubber Dry (dynamic)	> 0.38
	Sand Blast	Rubber Wet (static)	> 0.45
	Sand Blast	Rubber Wet (dynamic)	> 0.37

Test	Finish	Conditions of Test	Coefficient of Friction
ASTM C-1028	Sand Blast	Neolite Dry (static)	> 0.57
	Sand Blast	Neolite Wet (static)	> 0.49

The "sand blast" finish, less aggressive than other speciality finishes developed by Baultar, was conceived especially to make floor cleaning much easier and more economical than other types of floor coverings and finishes, while maintaining it's anti-skid properties (dry & wet), for the useful life of the product.*

** Note: The other Baultar speciality finishes are available if required, for areas such as Emergency Ramps and for stair nosing(s) and vestibules.*

E. SAFETY(continued)	
Flame Spread Index ASTM E-162	Is ≤ 13 (Surface Flammability, ABRASTOP™ Floor covering)
Critical Radiant Flux ASTM E-648	C.R.F. > 0.60 W/cm^2 (ABRASTOP™ Floor covering)
Specific Density of Smoke ASTM E-662	Specific Density of Smoke (Flaming Mode) For ABRASTOP™ floor covering: Ds(1.5 min) ≤ 5 Ds(4 min) ≤ 72
Toxic Gas Production SMP-800/801	Flaming mode at maximum-Abrastop™ only : CO ≤ 1500 PPM HCN ≤ 25 PPM HCl ≤ 25 PPM HF ≤ 10 PPM SO_2 ≤ 10 PPM NO_2 ≤ 10 PPM $COCl_2$ ≤ 10 PPM
Fire- Tests NFF-16-101 P-92-507 NFF-P95-501	Classification obtained with the ABRASTOP™/BEE-LITE™: M_2F_1

APPENDIX B:

CORE-CELL SPECIFICATIONS

ATC

Technical Data Sheet

CORE-CELL®

October 1997
(supersedes March 1997 version)

LINEAR STRUCTURAL FOAM

Core-Cell is a linear polymer foam that is non-friable, tough, rigid, and has a closed-cell structure. Core-Cell foams are used as structural sandwich core materials and provide low weight, excellent stiffness, and structural integrity under dynamic loads. Core-Cell foams have high shear elongation and impact strength. Core-Cell foams retain their mechanical properties even in the higher ambient temperature range. The insulation values are constant over time due to a controlled CFC-free foaming process. Core-Cell foams are compatible with polyester, vinylester, and epoxy resins. For prepreg and postcure applications, we supply Core-Cell "P" Series on special order. Densities above A1200 (A1500, A1800) can also be supplied. For all processing, consult the ATC "Process Instructions" and conduct appropriate tests.

TYPE	ASTM		A 300*	A 400*	A 450	A500*	A 550	A 600*	A 800	A 1200
Density, min.	D1622 Nominal	kg/m^3 lb/ft^3	50 3 - 4	60 4 - 4.5	70 4.5 - 5	80 5-5.5	90 5.5 - 6	100 6 - 7	130 8 - 9	200 12 - 13
Compression Strength	D1621	psi	63	84	100	125	157	194	317	584
Compressive Modulus	D1621	psi	2,132	2,654	3,165	3,888	4,495	5,148	7,520	18,408
Tensile Strength	C 297	psi	150	182	193	238	259	300	346	468
Shear Strength	C 273	psi	96	125	135	142	166	191	241	286
Shear Modulus	C 273	psi	1,699	2,475	2,586	3,116	3,339	4,186	5,390	6,555
Shear Elongation 77ºF (25º C)	C 273	%	60	60	60	60	60	60	50	40
Shear Elongation at 32ºF (0ºC)	C 273	%	40	40	40	40	40	40	35	30
Flexural Strength	D 790	psi	173	232	269	325	392	432	591	1,024
Flexural Modulus	D 790	ps	7,458	9,934	11,363	13,605	15,645	16,688	23,853	42,441
K-Factor R-Value (1")	C 518	BTU in./ $ft^2/h^\circ F$	.223 4.48	.231 4.33	.235 4.25	.240 4.16	.245 4.08	.250 4.0	.268 3.73	.316 3.16

* Type Approved by the American Bureau of Shipping. Accepted by Lloyd's Register of Shipping

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