FTA RESEARCH
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Design & Development of the LCO-140H Series Hydraulic Hybrid Low Floor Transit Bus

BUSolutions Final Technical Report

SEPTEMBER 2012

FTA Report No. 0018
Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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13. ABSTRACT

Automation Alley, Altair, and the Federal Transit Administration (FTA), in a public-private partnership, teamed up to advance a new transit bus initiative that would improve America's local and regional transit systems while requiring no infrastructure upgrades to operate. The goal was to develop a significantly lighter-weight, heavy-duty bus design that yields superior fuel efficiency to conventional buses at a lower lifecycle cost. The four main areas of focus for reducing the lifecycle cost of the new bus were purchase price, fuel economy, scheduled maintenance, and unscheduled maintenance. The results yielded the Altair ProductDesign LCO-140H hydraulic hybrid bus. A physical technology demonstration vehicle that is projected to have a 20 percent lower purchase price than most electric hybrids and saves over 30 percent in total lifecycle costs. The LCO-140H is projected to even save 20 percent in lifecycle costs over a basic non-hybrid diesel bus. Fuel economy test results showed a 110 percent improvement in fuel economy as compared to the average non-hybrid diesel bus, and over a 30 percent better fuel economy than the best-in-class hybrid electric bus results found in the Altoona database. The net result is that this design enables a transit authority to reduce their reliance on oil and save money while doing it.

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FOREWORD

Transit authorities today face many challenges. Operating costs, especially fuel costs, are on the rise, making it ever more difficult to meet operating budgets without subsidies. Public and political pressures continue for more efficient service with reduced environmental impact and less dependency on oil. The transit industry could benefit from a solution that significantly reduces costs and dramatically improves fuel economy without expensive and prohibitive infrastructure requirements.

Automation Alley, Altair ProductDesign, and the Federal Transit Administration (FTA), in a public-private partnership, teamed up to advance a new transit bus initiative that would improve America's local and regional transit systems while requiring no infrastructure upgrades to operate. The goal was to develop a significantly lighter-weight, heavy-duty bus design that yields superior fuel efficiency to conventional buses at a lower lifecycle cost. The four main areas of focus for reducing the lifecycle cost of the new bus were purchase price, fuel economy, scheduled maintenance, and unscheduled maintenance.

Since 2005, FTA issued $5.1 million in funding for BUSolutions, with additional program support provided by the Michigan Economic Development Corporation (MEDC) and Automation Alley, Michigan's largest technology business association, to produce the advanced technology demonstration bus. Altair, with the help of its partners and sponsors, successfully designed, fabricated, and tested the bus to validate the design and performance metrics.

The innovative design of the LCO-140H shows the benefits that can be gained by a simulation-driven design process when applied to a clean-sheet design of a transit bus. The subsequent build and test of the demonstrator has proven the results of a series hydraulic hybrid transit bus that more than doubles the fuel economy seen in the basic diesel buses today. With an average 6.9 MPG, as tested using the "Altoona" test procedures, this is 110 percent above the 3.3 MPG average fuel economy seen in diesel buses under the same test conditions. It is also 30 percent higher than the best full-size diesel-electric hybrid bus that was listed in the Altoona database.

This, however, was not done at an elevated cost to the transit industry. The LCO-140H is projected to have a 20 percent lower purchase price than most electric hybrids and save over 30 percent in total lifecycle costs. What is even more compelling is that the LCO-140H will save 20 percent in lifecycle costs over a basic non-hybrid diesel bus. For the first time, transit authorities and municipalities can reduce their reliance on oil and save money while doing it. This is the type of socially- and fiscally-responsible solution that would be beneficial to the transit industry.

ACKNOWLEDGMENTS

We would like to extend our thanks to a few specific individuals who made great contributions. Without them, the success of this program would not have been possible:

- James R. Scapa, Chairman & Chief Executive Officer of Altair Engineering, for support of the BUSolutions program and his valuable insight in guiding the project to its completion.
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- The BUSolutions Team for the many hours that went into the design, build, and testing of the LCO-140H and for the ideas contributed by its members.
- Sponsors and partners for providing us with valuable resources that went into the Hybrid Bus demonstrator assembly:
  - Platinum Sponsors: Parker, Meritor
  - Gold Sponsors: Meritor WABCO, PRAN, Sika
  - Silver Sponsors: Cummins Bridgeway, Haldex, LADD Industries, Shaw Development, TENNECO, USSC, Williams Controls, Alcoa, Carrier

ABSTRACT

Automation Alley, Altair, and the Federal Transit Administration (FTA), in a public-private partnership, teamed up to advance a new transit bus initiative that would improve America's local and regional transit systems while requiring no infrastructure upgrades to operate. The goal was to develop a significantly lighter-weight, heavy-duty bus design that yields superior fuel efficiency to conventional buses at a lower lifecycle cost. The four main areas of focus for reducing the lifecycle cost of the new bus were purchase price, fuel economy, scheduled maintenance, and unscheduled maintenance. The results yielded the Altair ProductDesign LCO-140H hydraulic hybrid bus: A physical technology demonstration vehicle that is projected to have a 20 percent lower purchase price than most electric hybrids and saves over 30 percent in total lifecycle costs. The LCO-140H is projected to even save 20 percent in lifecycle costs over a basic non-hybrid diesel bus. Fuel economy test results showed a 110 percent improvement in fuel economy as compared to the average non-hybrid diesel bus, and over a 30 percent better fuel economy than the best-in-class hybrid electric bus results found in the Altoona database. The net result is that this design enables a transit authority to reduce their reliance on oil and save money while doing it.

EXECUTIVE SUMMARY

Transit authorities today face many challenges. Operating costs, especially fuel costs, are on the rise, making it ever more difficult to meet operating budgets without subsidies. Public and political pressures continue for more efficient service with reduced environmental impact and less dependency on oil. The transit industry could benefit from a solution that significantly reduces costs and dramatically improves fuel economy without expensive and prohibitive infrastructure requirements.

BUSolutions, a public-private advanced transit bus development initiative by Altair ProductDesign, Inc., has yielded an innovative solution to the challenges that confront America's local and regional transit systems—the world's first series hydraulic hybrid bus, the LCO-140H (Low Cost of Ownership–1st 40-foot Hybrid).

The inspiration behind Altair's BUSolutions program initiative was driven by its global product development consulting organization, Altair ProductDesign. With an active consulting practice in the transportation industry, it became clear from research into the transit industry that the business challenges faced by transit agencies required an entirely new bus development process and design.

Through a "clean-sheet" design approach, the extremely lightweight, heavy-duty bus design yields more than twice the fuel efficiency of conventional buses at a lower lifetime cost. This is a first for any hybrid bus. Requiring no infrastructure upgrades to operate, the LCO-140H is an attractive option for transit authorities to cost-effectively upgrade aging fleets with hybrid vehicle technology.

Based on the merits of the innovative design and predicted performance benefits, in 2005, Altair partnered with Automation Alley, Michigan's largest technology business association, to explore government grant opportunities to support the physical build and testing of a technology demonstrator to validate the design. As a result, the program attracted the attention of officials from the U.S Department of Transportation (DOT) and the Federal Transit Administration (FTA). Since 2005, FTA has provided $5.1 million in funding for the BUSolutions program, with additional program support provided by the Michigan Economic Development Corporation (MEDC) and Automation Alley, to produce a prototype demonstrator of the bus concept.

From its inception, the BUSolutions program has continually involved industry experts from the manufacturing segment, transit authorities and rider advocacy groups to ensure that the program goals align with industry needs. Close cooperation and guidance were also provided by FTA in a partnership that continually adjusted the program goals to remain relevant and up-to-date with transit industry needs.

What started as an internally-funded "stretch" project today has resulted in an industry-first, series hybrid-hydraulic bus design that is ready for manufacture.

Having successfully completed the testing phase to validate the design and performance metric, BUSolutions' LCO-140H is the lowest cost, most fuel-efficient hybrid bus on the road today.

The LCO-140H yields fuel economy of 6.9 MPG on the industry standard ADB duty cycle, which is 110 percent better than conventional diesel buses on the road today and 30 percent better than the best-in-class electric hybrid buses available today. More importantly, the bus will cost over 20 percent less than a conventional diesel bus to own and operate over its life and over 30 percent less than an electric hybrid. For the first time, transit authorities and municipalities can reduce their reliance on oil and save money while doing it.

SECTION 1

Introduction

Problem Statement

The Federal Transit Administration (FTA) desires an upgrade to the modern transit bus that will provide a more efficient service to the public ridership while minimizing operating costs, fuel consumption, and environmental impact. Currently, U.S. public bus transit authorities require in excess of $19 billion in state and local subsidies and $7 billion in federal subsidies to meet capital and operating budgets.

Objective

Altair and FTA, in a public-private partnership, teamed up to develop an extremely lightweight, heavy-duty bus design that yields superior fuel efficiency of conventional buses at a lower lifecycle cost while requiring no infrastructure upgrades to operate. The four main areas of focus surrounding the lifecycle cost were purchase price, fuel economy, scheduled maintenance, and unscheduled maintenance.

Further, a technology demonstration vehicle would be built to showcase the claims of the program. This would include fuel economy testing in a format that would offer a comparative value to current industry offerings. In the end, the new bus would be an attractive option for transit authorities to cost-effectively upgrade their fleets with hybrid vehicle technology.

Background

In the early 2000s, Altair was working on an internal stretch project, where selected staff with a history in the public transit arena worked to show how optimization and other technologies and design processes Altair developed for the auto industry could benefit the transit industry. The internal program was called BUSolutions.

Being that Altair is a leading global provider of technology through its advanced engineering software, on-demand computing technologies, enterprise analytics solutions, and industry leading product design team, the primary goal of this program was to demonstrate the benefits of Altair's core technologies.

The endeavor began by composing a case study of the optimized monocoque structure using OptiStruct, HyperWorks' analysis and optimization tool. Because this component of the bus combines both the body and chassis to form a single frame, it is the single largest component on the vehicle and, therefore, provided the greatest opportunity to reduce weight. Before the optimization could begin, the loads and boundary conditions for the analysis run needed to be identified. Altair began extensive research to understand these variables.

As Altair successfully has done for decades with its customers, it analytically demonstrated that a significant amount of weight savings could be achieved in just the structure alone. Other areas were approached to optimize, and system engineering began on many sub-components of the bus. Before long, Altair had a unique design concept for a lightweight bus.

Innovation does not end with just a lighter design, and Altair understands that, to demonstrate a viable product, all aspects of the product requirements must be considered. The product requirements are defined by the owners, operators, and riders of the transit bus and embodied in the specifications written by the regional transit authorities (TAs). In today's economy, the majority of these TAs are subsidized by local, state, and federal government. A significant portion of this comes from an FTA subsidy providing 80 percent of the capital costs of the vehicle. This federal investment allows more buses to be put into service for the same capital cost to the TA. The TA's fiscal results are significantly driven by the total lifecycle cost for a bus. This primarily includes vehicle purchase price, vehicle maintenance costs, infrastructure costs, and fuel costs. Altair analyzed these areas and identified opportunities to reduce the lifecycle cost of the bus during the design process.

This internal study resulted in an impressive improvement to the design of a basic diesel transit bus. Early in 2005, this study was brought to the attention of southeast Michigan's regional congressional delegates, who decided it was appropriate to fund the validation of this design through congressional earmark funds. The primary purpose of the funding was to complete the bus design and build an advanced technology demonstrator to verify the results through testing.

Research Approach

Altair's approach to research for this project can be broken down into five categories. First, Altair used the resources and documentation provided by the American Public Transportation Association (APTA). Second, it called upon respected transit authorities throughout the United States for a thorough understanding of the challenges of the industry. Third, it talked to current industry suppliers to understand the product contributions to the overall goal. Fourth, adequate benchmarking was performed to understand the current offerings in the industry. Last, an advisory board was formed, comprising industry professionals from both the public and private sectors.

APTA

APTA is a non-profit organization that serves as an advocate for the advancement of public transportation programs and initiatives in the United States. Altair became a member of APTA, had staff sit on its committees, read its publications, attended its conventions, and visited its triennial expositions.

Additionally, APTA publishes a document entitled *Standard Bus Procurement Guidelines* [1] (informally known as the "White Book"). This document, which was developed using a cross-section of representatives from the public and private sectors of the public transit industry, outlines a request for proposals for a negotiated bus procurement contract. It is a close as one can get to an industry standard form for the acquisition of buses for the American market. Altair used this document to guide it through industry expectations.

APTA's vast membership directory and networking opportunities also proved to be a valuable asset to the program. With the triennial APTA Expo being the world's largest trade show for the public transportation industry, the "who's who" of bus manufacturers, suppliers, and technology meeting together under the same roof is an outstanding opportunity to research all facets of the industry.

Transit Authorities

Altair was fortunate to have the cooperation of many TAs throughout the program. From New York, Los Angeles, Houston, Chicago, Detroit, and many others, transit authorities across the United States opened their doors to the BUSolutions program. Some allowed Altair staff to perform ergonomic research by job shadowing and interviewing their drivers and maintenance crews throughout a typical day. Others offered mentoring opportunities with key employees of their organizations. All were helpful in understanding the key areas of concern that, if addressed, had the most potential to impact the TAs' bottom lines.

This approach allowed Altair engineers a first-hand look at the industry. The ability to discuss the product directly with the end user gives insight that is not available anywhere else. Whether talking to bus drivers about the features they want and the inefficiencies that hinder their job on a daily basis, or to the maintenance crew that struggles with routine maintenance or observes reoccurring problems on a daily basis, these interviews offered is a substantial learning opportunity.

Industry Suppliers

Leveraging current industry suppliers was essential in achieving the key goals of the program. Whether the supplier visited Altair or vice versa or a meeting was held at one of the many bus conventions or data were simply collected from their website, great pains were taken to identify the optimum configuration of off-the-shelf components in the industry today.

Through the use of decision matrices, suppliers were researched and their products were put head-to-head with their competition. The goal was to find the component that contributed to the lowest cost of ownership. Cost, weight, function, accessory load, durability, aesthetic value, and optimum packaging ability were all specifications that were examined and compared.

Benchmarking

Current industry buses were benchmarked in two ways. First, physical testing was performed by Altair on an industry-leading bus. This required Altair to rent a bus and take it to a proving ground to test, which allowed Altair engineers the chance to drive, instrument, and evaluate a bus that is leading today's market. Through Altair's connection with TAs, Altair engineers frequently rode buses and were given the opportunity to perform static inspections of buses. This opportunity furthered the learning process by giving the portion of the team that had not come from the transit industry an opportunity to fully immerse themselves in the product they were set out to improve. A photo of the benchmark bus tested and the drivers' area where an instrumented steering wheel used for vehicle dynamics data collection can be seen in Figure 1-1.

Figure 1-1

Benchmark bus and drivers' area test instrumentation setup

Second, FTA's new model bus testing database was investigated. The Altoona Bus Research and Testing Center operated by Penn State University is responsible for performing unbiased and accurate comparisons of all bus models where TAs have used subsidized federal funding for procurement. Its extensive public database enabled Altair to not only compare standard technical specifications of the bus market, but also testing results that capture vehicle performance, maintainability, structural performance, fuel economy results, noise levels, and more. From here, a matrix was developed that highlighted specifications, their averages, and the industry bests.

Advisory Board

Altair assembled a team of industry professionals from across the United States, including an FTA representative, operations and maintenance managers of top TAs, a former president of a bus manufacturing company, a CEO of a current bus rebuilding corporation, a transit advocate organization representative, and more. This team became the BUSolutions Advisory Board. They met on a regular basis and discussed the program's progress, gave insight on critical decisions, and shared personal experiences surrounding all aspects of the transit industry. Board members made themselves available for impromptu phone discussions and, routinely, topics were discussed via a dedicated e-mail group.

Although this was similar to the TA research approach, this furthered discussion beyond the end user. Topics covered both the technical and business issues. Industry engineers, business professionals, and the public's voice were all heard in these roundtable discussions. This was an effective way for Altair to engage both the public and private sectors simultaneously to minimize the chance that an outside voice or viewpoint was left off the table. Members of the Advisory Board included:

- Marcel Belanger, General Engineer/Program Manager, FTA
- Daniel D. Morrill, President, Midwest Bus Corporation
- Michael Dawley, Assistant Superintendent, City of Detroit, Department of Transportation
- Marvin Perkins, Director of Operations/Maintenance, SMART
- Ed Kravitz, President/CEO, ENJAK
- Michael A. Bottone, Jr., Director, Vehicle Technology, Los Angeles County Metropolitan Transportation Authority
- Mike Liptak, Technical Services, Houston Metro
- Transportation Riders United, Public Transportation Adversary Group, Detroit, MI

SECTION

2

Concept Developments

Ergonomic Research

To gain a more comprehensive understanding of a bus user's experience, bus drivers, passengers, and maintenance personnel were studied in their own environments. This method of research involved not only participant observation but face-to-face interviewing. This uncovered the wants and needs of the participants as they view the transit bus experience. While engineers typically develop concepts with focus on tangible goals that assist with meeting targets, it was felt that there were more areas not being explored that could directly or indirectly benefit the lifecycle cost of ownership.

Contextual Observations/Interviews

Bus drivers and riders were shadowed for the length of a driver's shift. Observations began as the driver arrived at the transit authority, visited his/her locker, began the daily pre-inspection of the bus, and on to the first route of the day. It continued through breaks and lunch. In total, four observational sessions of this type were conducted on different routes with different drivers. Each session consisted of two Altair team members, one from the Industrial Design team and the other from the Product Design team. This allowed for opinions and ideas to be taken away from both the creative and engineering side for each session. Alternate employees were used in subsequent sessions so that no pair was teamed up for more than one day.

The observations and interviews conducted were used to understand the needs, wants, and desires relative to drivers' and riders' daily experiences on the bus. Riders would often overhear conversations and voluntarily interject their thoughts on the subject. Many photographs were taken, and a video camera was installed above the driver to record driver control interactions. Although interviews were helpful to answer the basic questions about their time on the bus, the most useful information often came from the "fly on the wall" approach.

The drivers' perspectives were very similar. They wanted a quieter, more comfortable driver's area that made their day go by easier. Most adapted to the shortcomings of their environment, overlooking the fact that they were even being hindered. The most obvious problem from a third-party perspective was the lack of storage for the driver, leading to a cluttered driver's area. Figure 2-1 shows two examples of cluttered driver's areas; the left photo shows a plastic bag strung from a driver control to a driver control that contained the driver's lunch and snacks for the long day. Also shown is another location for a lunch box, tethered to a stanchion. On the right is a photo of a clipboard containing the driver's route information, daily checklist, and other employer-supplied information that has been placed on top of the instrument panel during vehicle operation. In this location, many gauges and feedback controls are obstructed, including the speedometer. This clipboard remained in this location throughout the entire shift.

Figure 2-1

Adaptation made to driver's area: driver's area clutter (left), clipboard (right)

Other feedback and observations surrounding the driver are summarized from all the routes as follows:

- Rider troubles with fares and the farebox slow down the route time and cause added stress for the driver. Riders often do not understand the process or fee structure.
- During hours of low light, riders have trouble seeing the farebox and struggle with inserting money. This also slows the route time, causing the driver to get behind schedule.
- The driver's seat needs to be comfortable with good cushion support.
- The bus ride is extremely noisy
- The bus interior was dark in color. The driver requested to have lighter colors to brighten the mood of both them and the riders.
- There was no place to store a lunchbox. Most drivers bring their lunch with them on the bus.
- There was no place to put jackets, coats, or umbrellas.
- There was no place to store clipboards or employer-supplied forms.
- There was no place to put a beverage, coffee cup, or water bottle.
- Drivers wanted more interior visibility of passengers behind them and near the rear door, both for their personal safety and the safety of the riders.
- The most-used driver controls should be put closest to the driver.
- The A-pillar is too large, often causing a blind spot that could obstruct a pedestrian or full-size car.
- The exterior mirrors should all be heated and electronically adjustable; some drivers are too short to manually adjust tall mirrors themselves.

Unlike drivers' perspectives, passenger perspectives varied greatly. Some passengers were content to come aboard, put on their headphones, and listen to music during their commute. Others were more engaging and desired to strike up a conversation with other riders. Most enjoyed their personal space, and a double set of seats rarely carried two passengers, even if it meant the passenger had to stand during the commute. The largest concern for passengers was knowing when to get on and off the bus. During one session on a rainy, humid day, the side windows fogged up, making it impossible for passengers to see out. This caused much commotion, as there were many false stop requests that morning.

Other feedback and observations surrounding the passengers are summarized from all the routes as follows:

- Passengers would like larger windows.
- Bus ride is extremely noisy and loud.
- Bus was dirty in areas where it seemed difficult to get to or clean.
- Hand rails at ingress/egress points were lacking height and position to accommodate passenger needs.
- Passenger seats could use more padding.
- Better handicap access and wheelchair tie-down capabilities are needed.
- Passengers would like buses to run on time every day.
- More effort could be put into the interior to make it more aesthetically pleasing.
- Passengers missed stops because they were unannounced and it was difficult to see out the windows to look for street signs.

Altair compiled this information and used it to aid in the development of the bus. The major take-away was that minor changes to the bus design could increase driver comfort and ability that would directly or indirectly reduce the cost of ownership. Further, improving the passenger environment and interfaces would encourage increased ridership, which would generate more fares.

Maintenance Observations/Interviews

Maintenance facilities were visited to observe procedures, discuss issues, and interview maintenance personnel. Photo documentation was taken to capture high areas of concern from a maintenance and serviceability standpoint. Scheduled maintenance documentation was reviewed with personnel to understand where the most time was spent.

The recurring feedback from the maintenance personnel was that the engine compartment is too crowded and components involved in routine maintenance are difficult to reach. Bus models from different manufactures had individual quirks and were noted as individual model concerns and not industry concerns. These problems were noted so they were not replicated, but they were not targeted as key problems to fix.

The maintenance facility managers had a different tack to their feedback. It was mainly focused on keeping the buses in service. Overheating in extreme temperatures was a major concern. Keeping the drivers happy was a close second. It was frequently documented that if a driver was unhappy, every little thing that went wrong would take the bus out of service. If the driver was happy, only safety-related problems would cause the bus to come out of service. Safety-related problems were less frequent.

Maintenance managers explained where the most damage occurred to the bus, inside and out. The front right corner took the most damage; the side skirts below two feet off the ground were second. They acknowledged the complaints from the maintenance personnel and encouraged their resolution, but keeping buses on the road was the number one priority.

Design Space Mockup

A rough mock-up of the front end interior of the bus was constructed from the front wheels forward. Many supplier-specified components (seat, wheel, fare box, etc.) were used in this assembly. For those components that were not available, volumetric models were created to represent the overall geometry and critical interfaces for the supplier products.

This mockup was intended to aid in stimulating, communicating, and evaluating design concepts. Because exact dimensions were not necessary, this approximate envelope yielded a quick and inexpensive way to develop and evaluate concepts.

Further, this mockup allowed for drivers to assist in setting up controls that accommodated their needs, interests, wants, and desires, as well as evaluate Altair design concepts. In the end, this proved to be a valuable resource that assisted in developing an ergonomically correct, attractive, and easy-to-use driver's compartment.

Figure 2-2

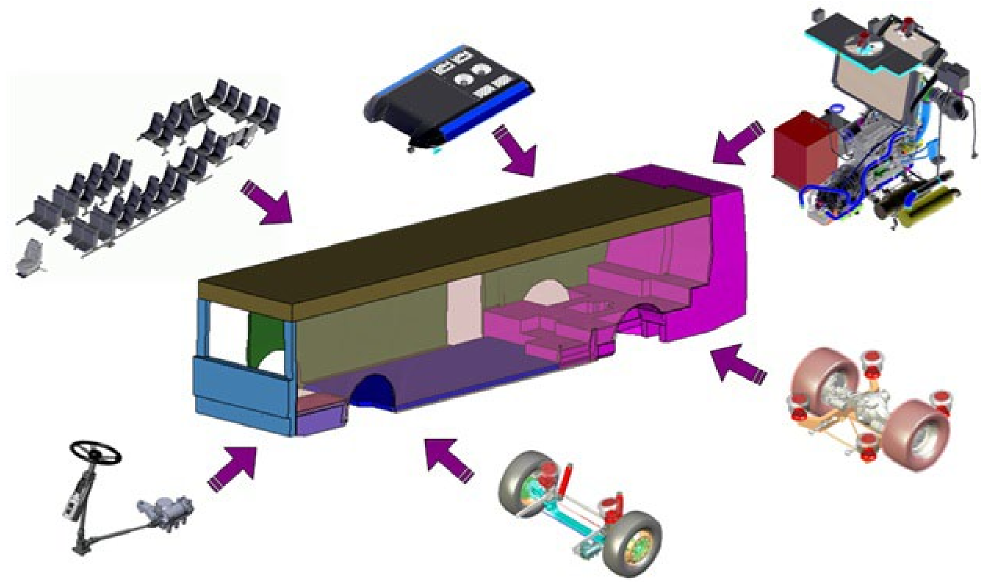
Driver's area design space mockup

Vehicle Level Targets

The vehicle architecture was the first area needing a list of requirements to be set up in order to begin topology optimization. This process mainly consisted of defining the physical size of the bus (height, width, length, etc.) and the package space for major systems (engine, axle, suspension, etc.) These packaging studies were free from structural constraints, allowing them to evolve rapidly. Figure 2-3 shows a pictorial view of the vehicle architecture concept development.

Figure 2-3

Vehicle architecture concept development



Next, APTA's procurement guidelines were reviewed and used to assist in the vehicle targets. The primary importance of following these guidelines was to produce a bus that had technical specifications that were consistent with industry standards. Many of the guidelines established a lower boundary that the targets were set to meet or exceed. Some examples of APTA guidelines that were exceeded by the LCO-140H were weight, maintenance, and fuel economy.

Industrial Design (ID)

Industrial designers were used to visualize, explore, and evaluate the ideas surrounding the program. From 2D sketches to 3D conceptual designs, ID allowed ideas to be communicated quickly. The exterior styling of the bus is the first impression one gets, and numerous designs were developed before the final design was selected. Four renderings from the early stages of the program can be found in Figure 2-4.

Further input led to a 3D conceptual design and a scaled, clay model mockup of the bus. These can be found in Figure 2-5. As the design was finalized, numerous people were consulted on the best look for the bus. The final conceptual design can be seen in Figure 2-6.

Figure 2-4

Early stage design renderings

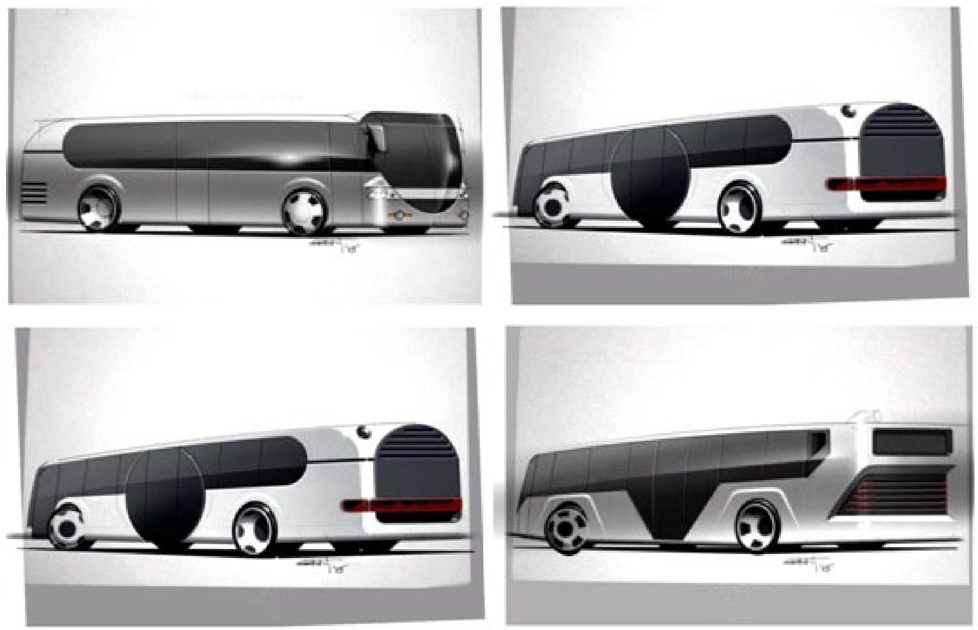


Figure 2-5

Early 3D conceptual design (left) and clay model of bus (right)

Figure 2-6

Final bus rendering

Altair Innovations

The ideation process used to formulate and compile innovations for this program was unique. On a project this large, extreme discipline is required to avoid collecting multiple broad-view ideas that do not focus on the enhancement or solution to an existing problem. If this occurs, many good ideas can be lost because the end result is not clear. The fact that this program started with a "clean sheet" was invaluable to its success, but it also meant that a requirements-based design strategy was essential.

A specific list of questions and criteria was established to concentrate the focus on the desired outcome. The focus for this program remained "to lower the cost of ownership." Altair did not want to "reinvent the wheel," but rather to use existing products and technology available and apply them in a more efficient way that would yield better results. Because of this, the ideation process was bounded and specific components were limited to change. For example, the internal combustion engine was labeled as an off-the-shelf product; therefore, designing a new engine was not on the table.

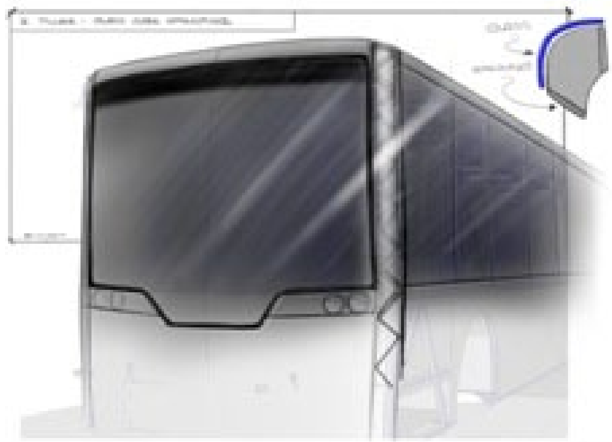
Visual brainstorming is an exercise that proved valuable in the ideation process. This method is similar to traditional brainstorming with one major difference: every idea must be expressed in a picture. Background data collected throughout the program, including the ergonomic research data collected, were brought to the visual brainstorming events to be used as thought-starters. Most of this data was pictorially displayed on screens or posted on walls. An experienced facilitator led each session, quickly going through the method. Multiple sessions were held. The goal was to, first, extract as many ideas as possible relative to the topic at hand. Then, a design decision matrix was used to help rank order the ideas and determine which to carry forward to the design concept phase. Once these designs were selected to carry forward, a final visual brainstorming session was held with extreme focus to fully refine the concepts. Further, those refined concepts were put into CAD and CAE tools were used (where appropriate) to qualify the design.

The following list contains some of the early design concepts that had merit but did not make it through the entire filtering process for the bus program:

- **Transparent A-pillar**. This idea came out of the ergonomic research where a driver complained that the A-pillar (the structural beam where the windshield and driver's side window meet) provided an unwanted blind spot for the driver. This solution delivered a truss shaped A-pillar with transparent glass inserts. A sketch of this idea can be found in Figure 2-7.

Figure 2-7

Transparent A-pillar design concept

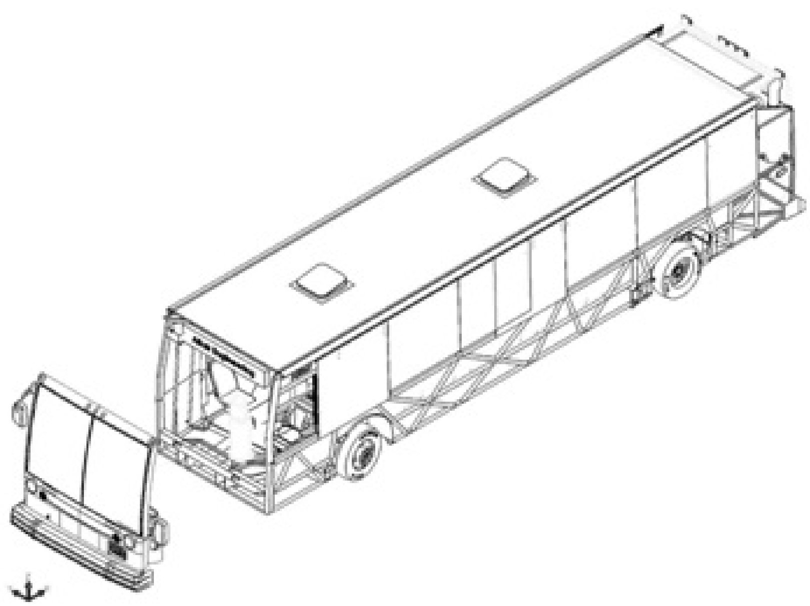


Because the total cost of ownership drove final design decisions, this idea was eventually omitted from the design as the cost to implement was higher than a simple A-pillar construction, and the benefits were difficult to quantify.

- **Removable front end**. This idea came out of the brainstorming efforts focusing on reducing manufacturing and repair costs. This solution provided a one-piece front end that would enable fabrication activities to occur at a separate station in parallel with the entire vehicle assembly line efforts. This allowed easier access to interior fabrication, resulting in reduced assembly costs. With the majority of accidents reportedly involving the front end of the bus, the front clip would be able to be replaced with a spare front end in the stock room, drastically reducing the time the vehicle is out of service. A rendering of this concept can be viewed in Figure 2-8.

Figure 2-8

Removable front-end design concept

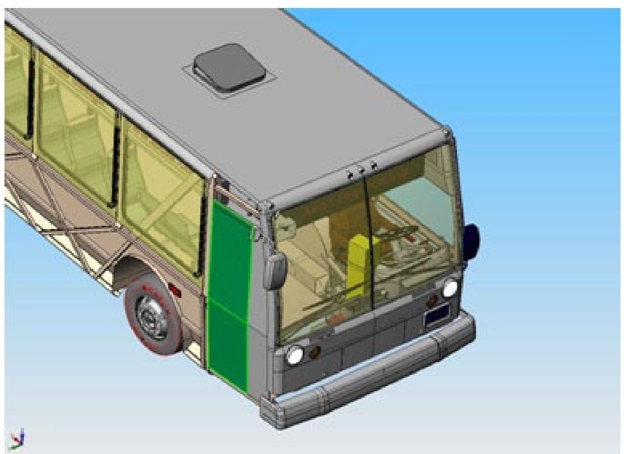


This idea, although with merit, should be implemented when a specific manufacturing strategy facility is identified. Many existing plants run buses through nose-to-tail, where this benefit would not be realized. Although not included in the final design, it is a feature that could be incorporated with relatively little effort.

- **Asymmetric front end**. This idea came out of brainstorming efforts to reduce accident rates. The solution provided a beveled structure starting at the rear of the front door moving forward to the windshield. Not only does the modification of the front right corner reduce weight and reduce the frontal area of the bus, which both have advantages related to cost of ownership, it trims the specific area of the front end in where the most damage occurs during front end accidents and collisions. Further, it can be said that with a corresponding wheelchair ramp matching the angle of the door, the access for wheelchairs is also improved. This area is shown in green in Figure 2-9.

Figure 2-9

Asymmetric front-end design concept

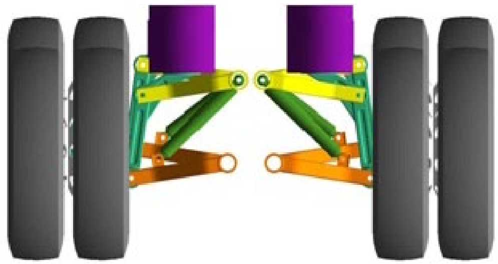


This idea also was discarded because it added some cost and it was difficult to quantify the benefits relative to the cost. Most of the additional cost came from needing asymmetrical front construction, including modifications to a purchased bumper. Also, the final design without this feature does allow complete wheelchair access as planned.

- **Independent rear suspension (IRS)**. This idea came out of brainstorming efforts to reduce maintenance costs. This concept received inboard brakes that would substantially reduce the service time of rear brake changes. This would also increase ride comfort of the bus patrons. An image of this design depicted in CAD can be seen in Figure 2-10.

Figure 2-10

Independent rear suspension design concept



This idea was pursued to some extent with the existing axle and suspension suppliers for the bus industry. Many of these suppliers are cautious about introducing new designs for warranty and fiscal reasons. As it was considered too large a departure from the goals of the program to provide a bus design that would immediately integrate with the existing transit authority and industry infrastructure, this idea was omitted.

- **Ultra-short driveshaft**. This idea came out of brainstorming efforts to increase the passenger-to-length ratio of the bus. Reducing the length of the driveshaft was found to have a direct effect on the overall length of the vehicle. To accommodate this, the U-joints had to accommodate severe angles, and the load would need to be taken up in a shorter distance across the shaft. The design overcame both of these concerns. A photo of a selective laser sintering (SLS) rapid prototype of this driveshaft is shown in Figure 2-11.

Figure 2-11

Ultra-short driveshaft SLS rapid prototype design concept

This idea was also pursued to some extent with the existing axle and suspension suppliers for the bus industry but was not continued for the same reasons.

Although some ideas were not included in the final design of the bus, many were. The following table shows a list of the design innovations that went through the ideation process and made it in the final design of the LCO-140H.

Table 2-1 *Design Innovations*

Innovation	Reduced Mass	Lower Purchase Cost	Increased Fuel Economy	Reduced Maintenance Time	Enhanced Driver & Passenger Comfort
Enhanced rear engine compartment layout	X	X		X	
Cool air corridor with roof air intake	X		X	X	
Intelligent decentralized multiplex system	X	X	X	X	
Integrated and removable HVAC unit				X	
Secondary windshield				X	X
Wireless diagnostic link				X	
Heated washer fluid					X
Obstruction-free HVAC vents					X
Super single tires	X		X		
Easy-clean floor				X	
Led replacement lights				X	
Kneeling lag time to acceleration			X		
Alternator/generator snorkel			X		
Outside access defroster unit				X	
Single piece balsa composite floor & roof	X		X	X	
Spray-on interior	X	X		X	
Tire pressure monitoring			X	X	
Fully forward seating main floor					X
Programmable display unit on I/P		X		X	X

Figure 2-12

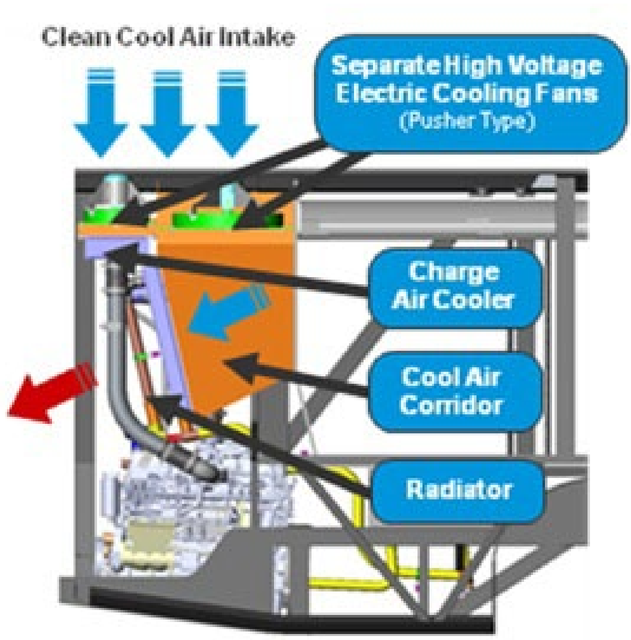
Wide-based tire on LCO-140H

An example of an innovation where systems engineering was coupled with new technology was the cool corridor in the rear engine compartment. Typically OEMs design cooling systems to perform just at the limit of capacity because of limited packaging space and significant horsepower draw of the system. Altair re-engineered the system to achieve heat rejection that is 10 percent above the capacity due to the fact that the number one cause of unscheduled maintenance leading to buses being out of service is engine overheating. Designing in a 10 percent safety factor, along with the other advantages of the cool corridor, substantially reduces the risk of engine overheating during the days where the temperature rises above seasonal highs.

Figure 2-13 shows how the cooling system works. An array of individually-powered, variable electric fans is positioned just below the roof above the cool air corridor. This reduces heat intake into the radiator by pulling the coolest and cleanest air possible into the cool air corridor. When the cool air corridor is charged, it exhausts the air through the oversized radiator. The aluminum radiator has half as many rows as a traditional brass/copper radiator, with twice the surface area, resulting in a 33 percent reduced mass. Due to the reduced core thickness and increased surface area, the power draw needed to operate the fans is dramatically reduced.

Figure 2-13

Side view of engine compartment showing air flow through cool corridor



Maintenance on the cool corridor is also reduced. Less core depth means less dirt accumulated. The cooling fans are automatically reversed daily to dislodge any dirt from the radiator core, plus the hot side of the radiator has open access from the rear of the engine compartment for easy cleaning. Last, the fans for the charge air cooler and radiator are separated because their duty cycles differ. This extends component life resulting in less maintenance as well.

An innovation that transcended the bus project was the integration of replaceable LED lighting tubes for the fluorescent light tubes. LED lighting lasts longer than fluorescent lighting and uses less energy, which saves on maintenance cost. One of the main goals of the program was to make a lower cost of ownership bus without changing the current infrastructure. The invention of the replaceable LED tube enables existing buses in the fleet to use the same light bulbs for existing units in their fleet as well as the LCO-140H. This eliminates the need to stock multiple models of replacement bulbs in the transit authority. This innovation inspired the creation of Altair subsidiary Ilumisys and a fluorescent tube replacement business. A photo of the LED lighting by Ilumisys is shown in Figure 2-14.

Figure 2-14

Replacement LED light tubes

SECTION

3

Design Process

The design process used in the BUSolutions program was as follows. First, a design concept needed to be solidified. This, in large part, was carried out in the concept development phase. Then, targets needed to be developed, reviewed, and documented. Once this was complete, primary CAD definition could begin. A design decision matrix (DDM) was created for each critical component to compare supplier offerings. Suppliers were identified in parallel efforts to the CAD definition process, and component placeholders were replaced with supplier CAD models when they became available. A Design Verification Plan (DVP) and Design Failure Mode Effects Analysis (DFMEA) were developed for each critical component and system. Finally, rough analysis or CAE was performed when appropriate on components and systems.

A matrix was set up to track the progress of each sub-system on the bus as it progressed through the design process. This acted as a "dashboard" to report to management the status of the program. An example of this matrix is shown in Table 3-1.

Begin Q1 2010 Sub-System	Targets Developed, Reviewed, and in Vault	Concept Documented	Suppliers Identified	BOM Populated	Industrial Design Consulted	Placeholder representation in CAD	Rough Analysis or CAE Complete	DDM Complete	DFMEA Created	DVP&R Created	Prime Candidate Concept Development Matrix Complete
01_00_00 Body	75%	75%	80%	90%	75%	75%	85%	50%	0%	0%	75%
02_00_00 Frame and Mounting	75%	75%	100%	100%	N/A	50%	75%	N/A	100%	100%	75%
03_00_00_Engine_	85%	85%	75%	75%	100%	75%	75%	N/A	100%	100%	75%
04_00_00 Suspension	70%	70%	92%	100%	N/A	75%	25%	50%	0%	65%	75%
05_00_00 Driveline	15%	100%	100%	0%	N/A	100%	N/A	15%	100%	100%	15%
06_00_00 Brake	6%	36%	38%	5%	N/A	8%	N/A	0%	N/A	98%	0%
08_00_00 Series Hydraulic Hybrid	60%	100%	100%	50%	N/A	80%	5%	50%	5%	5%	5%
09_00_00_Exhaust_	80%	80%	100%	75%	N/A	65%	N/A	N/A	100%	100%	80%
10_00_00 Fuel	75%	75%	100%	75%	N/A	50%	N/A	N/A	100%	100%	80%
11_00_00 Steering	50%	50%	50%	50%	N/A	65%	25%	25%	0%	67%	50%
12_00_00 Climate Control	100%	100%	100%	100%	100%	100%	N/A	100%	N/A	N/A	100%
13_00_00 Info Gauge Warning	100%	95%	21%	76%	30%	92%	0%	0%	0%	0%	91%
14_00_00 Electrical Power Supply	100%	100%	100%	100%	N/A	100%	N/A	N/A	N/A	N/A	100%
15_00_00 Radio Tape & Communications	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
17_00_00 Lighting	100%	100%	13%	100%	18%	100%	N/A	0%	N/A	N/A	0%
18_00_00 Electrical_	0%	0%	11%	0%	N/A	3%	0%	4%	0%	0%	0%
19_00_00 Public Interface	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

CAD Definition

Defining CAD is a requirement used to visualize the placement and relationships of the various parts in the subsystems. Initial place holders are used to represent key components in the bus. As the Bill of Materials (BOM) is populated and prime candidates are selected, the rough CAD is updated with Altair-designed and supplier data in order for subsequent analysis of the compatibility between interfaces to begin.

Some component locations are fixed with little room for compromise; these have a fixed CAD definition. The steering wheel shown in Figure 3-1 has a fixed CAD position relative to the driver's environment. Other components locations in the steering system, such as the miter gear box and intermediate shafts, are not defined up front and require the creativity of an experienced designer to package in available areas. The steering gear in the lower right must undergo a compatibility analysis with the suspension system in order to function properly.

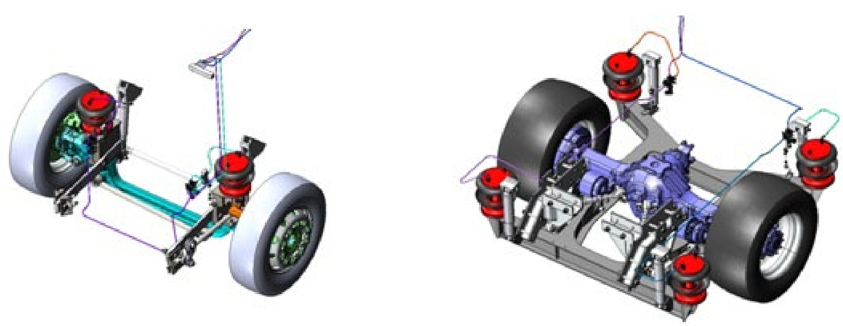
Figure 3-1

CAD of completed steering system

The suspension CAD definition required the identification of multiple attachment points for the air springs, shocks, and attachment linkages. Package protection was completed up front for dual rear wheel/tires referencing multiple supplier offerings. Due to the relative movement between the suspension and structure during suspension travel, multiple configurations of the CAD were compiled to fully define the design. Figure 3-2 below shows the final CAD for the front and rear suspension designs.

Figure 3-2

CAD of front and rear suspension



The body subsystem was broken down into 17 major subsystems. To simplify the design, they can be identified as interior or exterior. The exterior interfaces with multiple systems including climate control, lighting, hybrid, and public interface. This area has the most design freedom, with the only constraint being exterior boundaries in compliance with Federal Motor Vehicle Safety Standards (FMVSS). The CAD of the exterior subsystem is shown in Figure 3-3. The interior system was designed to accommodate the maximum number of seats possible. It also interfaced with multiple systems including info, gauge, warning, electrical, radio tape and communication, lighting, and public interface. The CAD of the interior subsystem is shown in Figure 3-4.

Figure 3-3

CAD of exterior body system

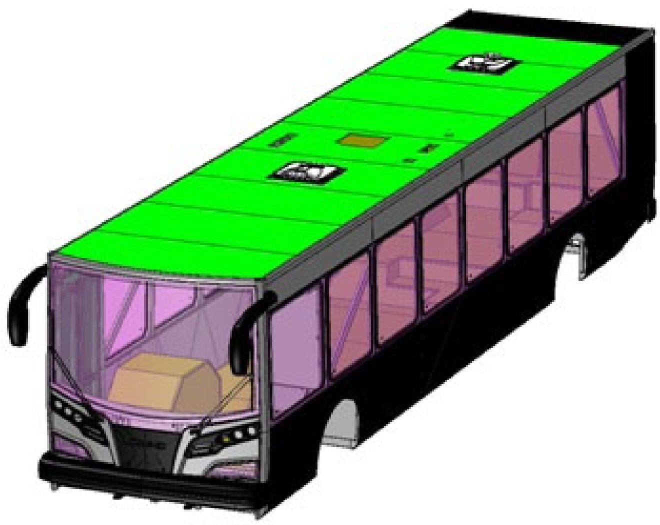
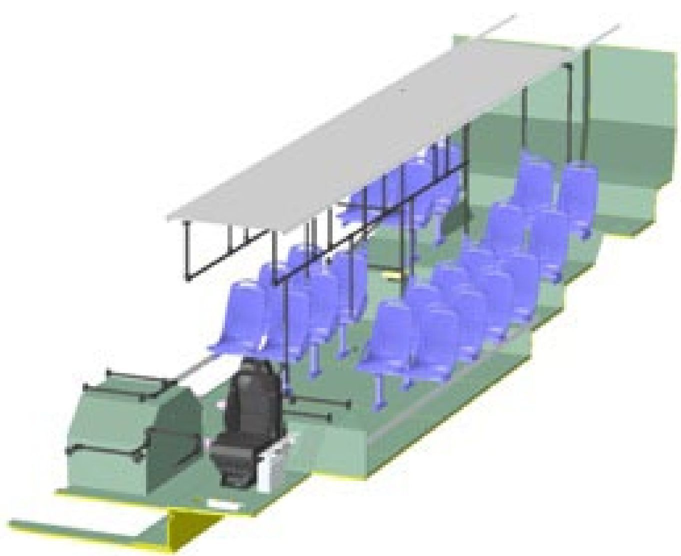


Figure 3-4

CAD of interior subsystem



Bill of Materials (BOM) Population

This phase in the development process is essential to define all the various components that make up the sub-assemblies in the bus. The BOM lists all of the components in a tiered/layered fashion associating the components with their respective sub-assemblies and over 100 categories of related information. It was essential to keep a live and up-to-date BOM as it drove CAD and procurement efforts throughout the program, along with cost and mass estimation as the design evolved.

The BOM was broken up into 16 major subsystems. A list of these subsystems is shown in Table 3-2. Each subsystem contained as many as six sub-levels of systems to give full detail of the assemblies. These subsystems were used in the matrix used to track program process.

Table 3-2

Systems in Bill of Materials

System ID	System Name
1	Body System
2	Frame & Mounting System
3	Engine System
4	Suspension System
5	Driveline System
6	Brake System
8	Hybrid System
9	Exhaust System
10	Fuel System
11	Steering System
12	Climate Control System
13	Information, Gauge, and Warning System
14	Electrical Power Supply System
15	Radio, Tape & Communications System
17	Lighting System
19	Public Interface

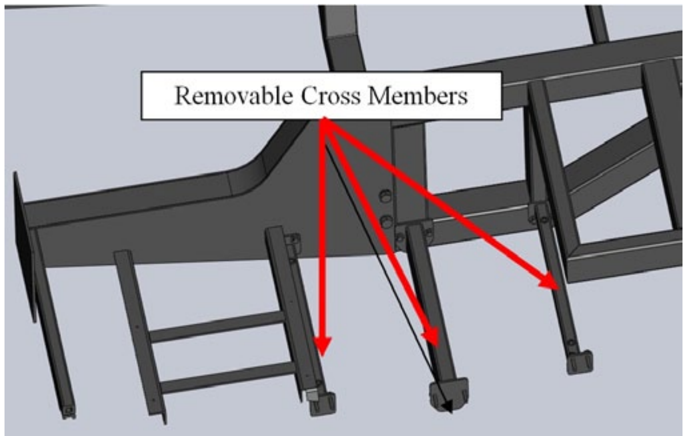
Compatibility and Interface Analysis

A critical stage in the design process was a compatibility and interface analysis. This ensured that the proper clearances were given between components and systems. Additionally, this was an opportunity to review accessibility during assembly and maintenance operations.

One component that required interface analysis was the fuel tank. The "L-shaped" fuel tank required two cross members to be removable to facilitate removal and re-installation for maintenance once the vehicle was assembled. The initial design was valid with only one removable cross member; however, once the bus was fully assembled, component removal was found to encroach on adjacent assemblies. These cross members are shown in Figure 3-5.

Figure 3-5

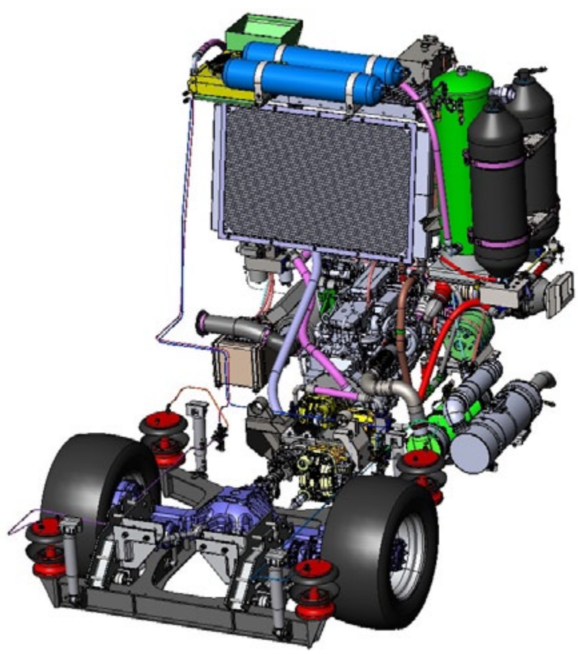
Fuel tank removable cross members



The most complex area on the bus is the engine compartment. Within this area, a part of nearly every major assembly has an interface. There are multiple maintenance compatibility examples such as filter replacements and fluid audits, as well as functional interfaces such as ensuring that the path for the cooling system airflow is unobstructed. All the compatibility checks were successful, and the interfaces are shown in the engine compartment design in Figure 3-6.

Figure 3-6

Engine compartment design



SECTION

4

System CAE

The program subscribed to a simulation-driven design approach. This enables the engineers to rethink systems for efficiency early in the program using industry leading analysis tools. By evaluating ideas early in the design process, better decisions are made that enable the delivery of an optimized solution that meets program goals. By starting with a "clean sheet," these ideas could be implemented without the interference of existing design constraints.

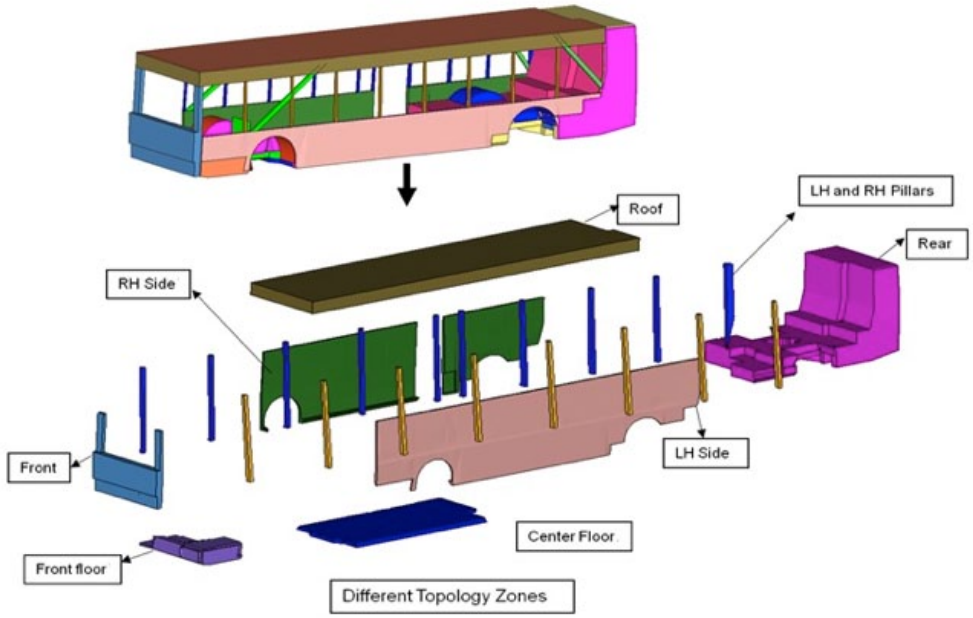
Topology Analysis

Topology analysis is a finite element (FE) based method used to generate the optimal load path definition for a component or subsystem (as is the case with the bus structure) when given the maximum amount of available package space to work with, without the constraints of a specific material or manufacturing process. The outcome of the analysis is independent of material type and manufacturing process. Manufacturing process constraints can be added to the simulation if it is desirable to work within the constraints of a specific manufacturing process, such as castings, to ensure the solution represents a manufacturable condition. The load path optimization process provides a design solution of maximum stiffness with the least material usage. Local component details then get refined based on the topology results. This is an important step in enabling mass targets to be achieved.

Multiple components of the bus were derived using topology optimization. The largest single component is the bus structure. The design space is derived by defining the maximum exterior volumetric shape of the bus from industry guidelines, from which volumes are subtracted for those subsystems that reside within the package space, such as the people package, wheels/tires, suspension and steering system, engine, etc. The design space was then constrained at the suspension mount areas. The load cases for the structure (e.g., gravity, braking, steering, passenger, and impact loads) were defined based on industry research and applied to the design space. The design space for the structure with topology zones is shown in Figure 4-1.

Figure 4-1

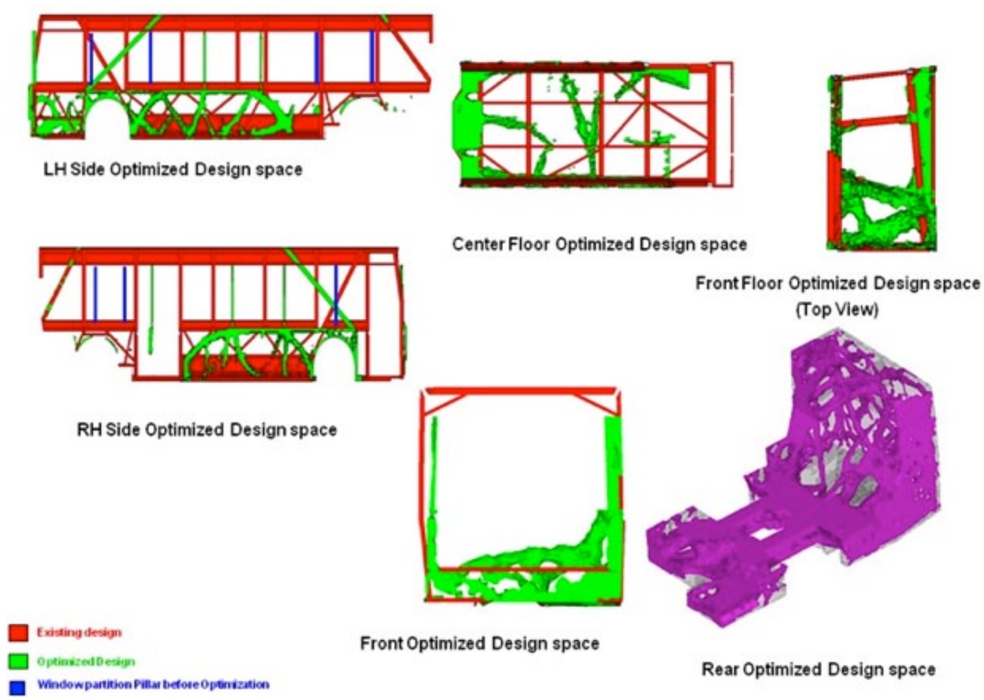
Defined design space for topology analysis



Once all of the constraints and loads are defined, the topology analysis can be performed. The results yield an organic shape similar to the characteristics of how a tree grows in nature or human bone growth. The topology optimized results are then put through a short iterative process where experienced engineers interpret the results to define structural members that best represent the topology. Examples of the topology optimization results are shown in Figure 4-2.

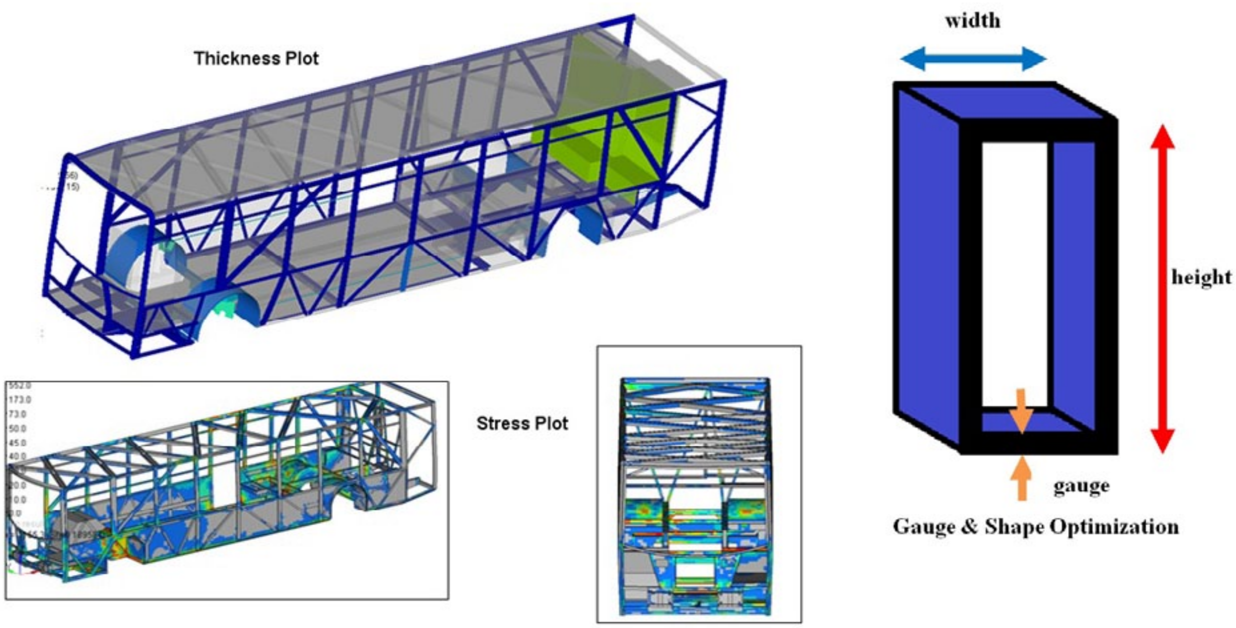
Figure 4-2

Topology optimization results



The next stages in optimization are gauge as well as shape optimization. This analysis defines the dimensions of the structural members. The results defined varied thicknesses throughout the structure. On components where common sections are used to fabricate the analyzed product, the results are compiled into a spreadsheet and consolidated to a manageable number of cross sections. The gauge and shape optimization results are shown in Figure 4-3.

Figure 4-3 *Gauge and shape optimization results*



Finite Element (FE) Modeling and Analysis

FE Modeling and Analysis is a mathematical simulation method used to guide the design process regarding structural performance, based on industry-wide standards for loading of bus structures. After every topology analysis, the structure of the bus is validated using FE Analysis methods. Hot spots (i.e., high stress levels) are identified, and subsequent iterative analysis will be performed to improve the design of the overall structural system. Normal modes analysis, discussed in more detail below, is also performed to evaluate modal characteristics of the overall structure so as to identify shortfalls to global stiffness targets and to identify areas for improvement.

Structural analysis was performed to evaluate performance for braking, engine torque, steering, standing passenger, front and rear towing, front impact, rear impact, and side impact load cases. Results from the front impact load case are shown in Figure 4-4. All stress results were below the yield strength of the material. The stress results are shown in Figure 4-5.

Figure 4-4
Front impact load cases

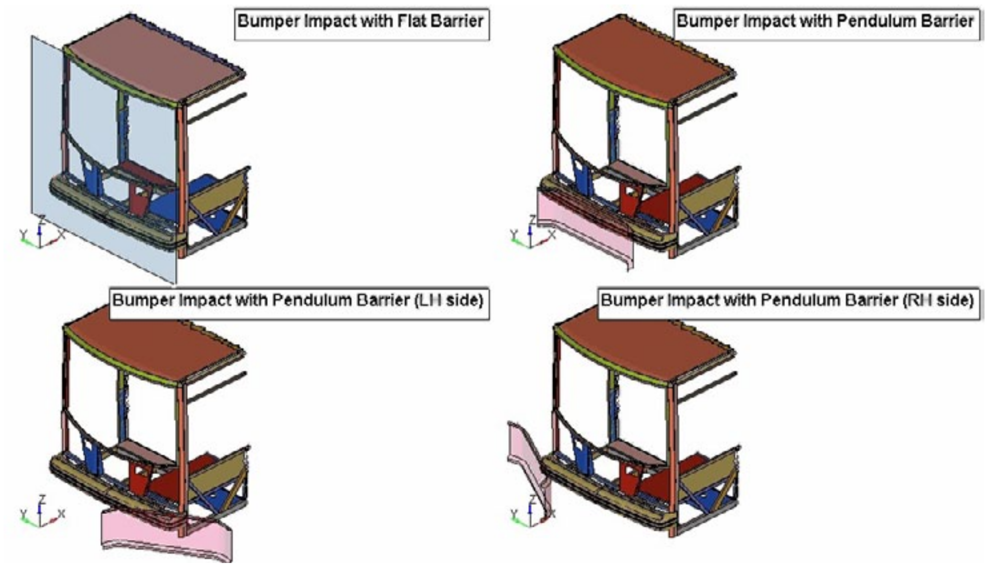
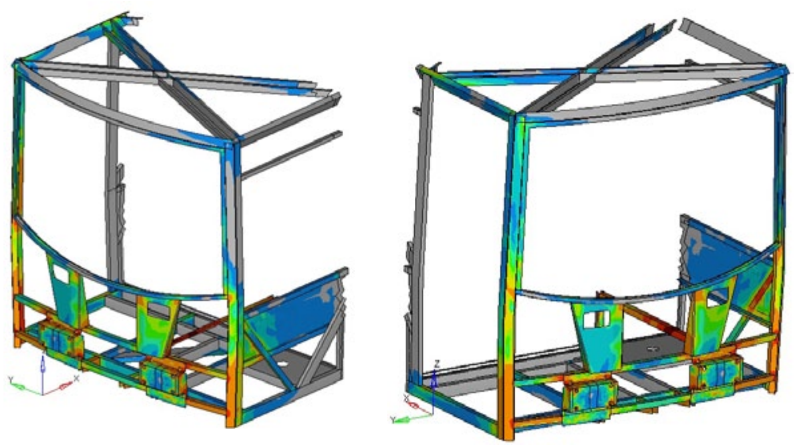


Figure 4-5
Front impact analysis results



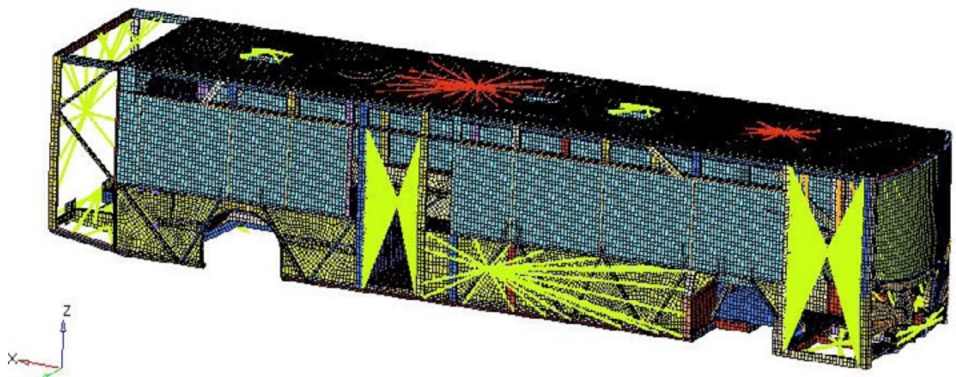
Powertrain Analysis

The powertrain of the LCO-140H and a control vehicle were modeled using Advisor and Simulink early in the design process to understand the key variables that influence fuel economy. Looking at variables such as vehicle weight, engine type, accessory loading, and hybrid system efficiencies allowed engineers to target key areas for improvement early in the design process. Various duty cycles were entered into the simulation to predict how the bus would perform on different routes. This enabled early comparisons to the industry to verify that program targets were achievable and tradeoff choices were made correctly.

Normal Modes Analysis

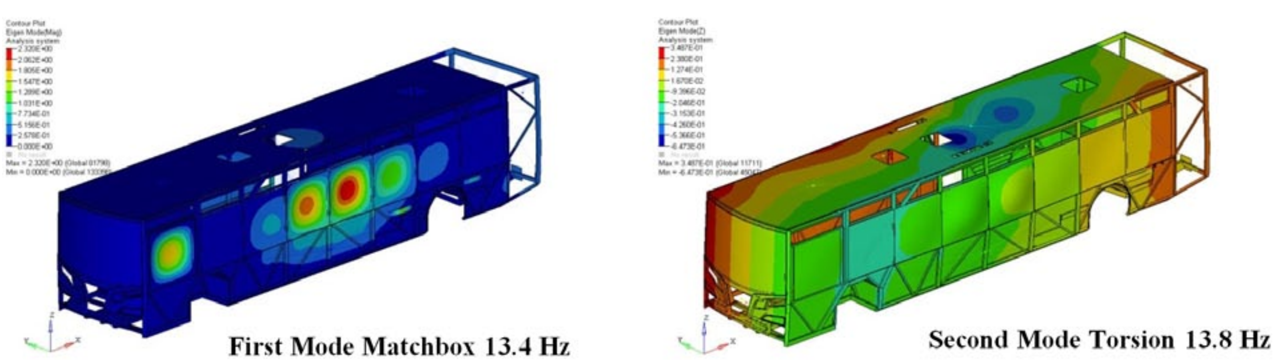
To understand the dynamic properties of the structure, a modal analysis was performed. It was set up to predict the structural vibration modes in the range of 0 to 20 Hz. The model was developed with point masses to reflect key components such as doors, HVAC, powertrain, etc. This model is shown in Figure 4-6.

Figure 4-6 *Modal analysis FE model*



The goal was to understand the frequency of the lowest mode shape because the lower modes are the most prominent. It is also important that the period at which the structure will naturally resonate does not match the frequency of other critical systems on the vehicle or unpleasant vibrations, noises, and/or even structural damage could occur. The first mode shape could best be described as a matchbox event at 13.4Hz. A matchbox event is when opposing sides of a box-like structure move in parallel planes but in reverse directions, similar to the movement of a traditional empty matchbox cover when pressure is applied to one side causing it to fold flat. The second mode shape was a torsion event at 13.8 Hz. The results are shown in Figure 4-7.

Figure 4-7 *Modal analysis results*

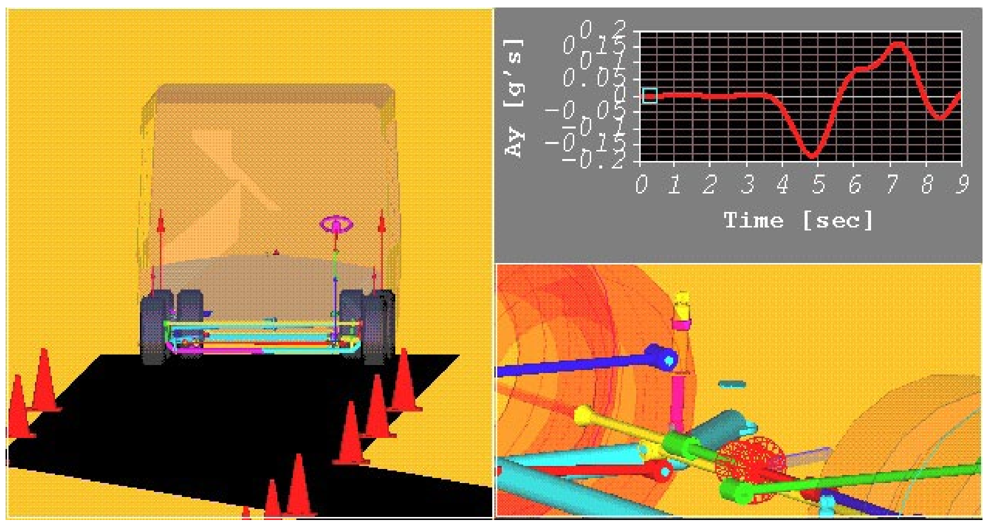


Full Vehicle Multi-Body Dynamics Analysis

The ride and handling characteristics of the bus were analyzed. The results produced dynamic loads that were used to define critical load cases for structural analysis. Further, the analysis assisted in the selection of damping components in the suspension to ensure a safe vehicle was produced. Figure 4-8 shows a Motionview model of the bus driving through an S curve.

Figure 4-8

Multi-body dynamics model



SECTION

5

Hybrid Powertrain Selection

The original design of the LCO-140 contained a conventional diesel powertrain. In 2009, the program goals and progress were revisited. In light of industry, market, and economic influences, decisions were made to change the powertrain to an advanced hybrid system. The primary driver for this change was the reduction in life-cycle cost, which is primarily achieved through the significantly increased fuel economy. A corollary benefit is significantly reduced CO_2 emissions. There were many hybrid offerings on the market, but the direction was to find the most effective solution available for this application and duty cycle.

Advanced Power Unit Research and Supplier Selection

A small team was assembled to research hybrid offerings. Intensive Internet research identified many possibilities. Expositions such as the Hybrid Truck Users Forum (HTUF) Expo were visited by team members; hybrid system suppliers were also visited. In addition, the EPA Advanced Research Group in Ann Arbor, Michigan, was consulted. In the end, the decision to pursue a hydraulic hybrid was made.

The hydraulic hybrid approach is untried in the transit bus industry. However, that is not what led to the decision to integrate it into a bus. There are many attributes of a hydraulic hybrid that make it an interesting choice for a transit bus; low system entry cost and lower maintenance costs are two. However, the main benefit that cannot be overlooked is power density, the amount of energy that can be transferred during a period of time.

All hybrid vehicles use regenerative braking. This allows the system to reclaim energy that is otherwise lost to heat during the braking cycle. When an electric hybrid goes into a braking event, the vehicle inertia is slowed, in part, by a having the wheels turn a linkage back to the electric motor, essentially using it as a generator to charge a battery. Hydraulic hybrids capture that energy in the same braking event and store it in the form of fluid power. The advantage of the hydraulic hybrid approach is that this method is able to store much more energy quickly, making it more suitable for heavy vehicles with high stop-go duty cycles.

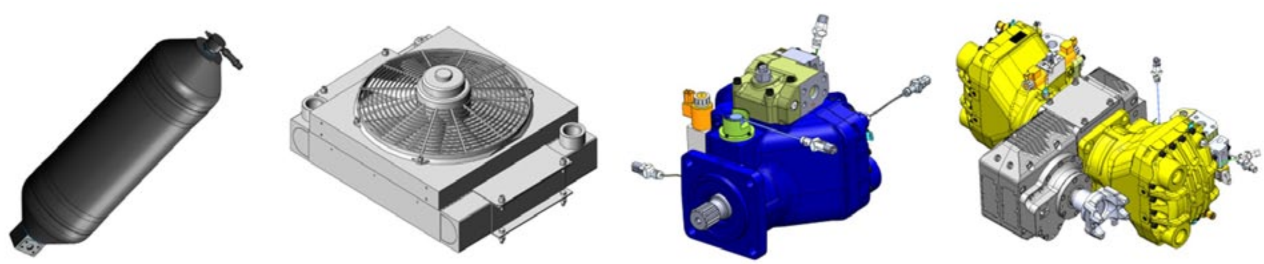
Two configurations were available to deliver the power from the hydraulic hybrid—series and parallel. A series system inserts the hybrid in line with the driveline. This essentially breaks the mechanical connection between the engine and the drive axle. A parallel system allows the hybrid to reside next to a more traditional drivetrain. Here, a direct drive configuration exists, coupling the engine to the drive axle. Both systems have benefits. Given the typical duty cycle of a transit bus (low average speed/high number of stops per mile), analysis showed that the series system would provide the optimum fuel economy. This was largely due to the fact that when the engine is decoupled from the drive axle, there is no longer a requirement to match engine RPM with vehicle speed. This enables the engine operation to run at the most efficient RPM to yield optimum fuel economy.

Next, a supplier had to be chosen. At the time, three major U.S. suppliers were developing and investing in the production of hydraulic hybrids for this class of vehicle. Meetings were held with all three, at the director level and above. Of the three, the supplier that was the furthest along, could meet program timing and targets, and had targeted the bus market in future business plans was Parker Hannifin. Through joint efforts and analysis, the series hydraulic hybrid was chosen for implementation in the LCO-140H.

System Analysis and Development

The majority of the system components were available from Parker offerings and their identified suppliers. These included the bladder accumulator, hydraulic cooler, engine mounted pump, and gearbox with pump/motors. These components are shown in Figure 5-1. The CAD data for these components was secured from Parker and used for preliminary packaging of the hydraulic hybrid system in the bus. Some initial analysis was completed before the entire system could be specified in order to understand what system capacity would yield the optimal results from the system.

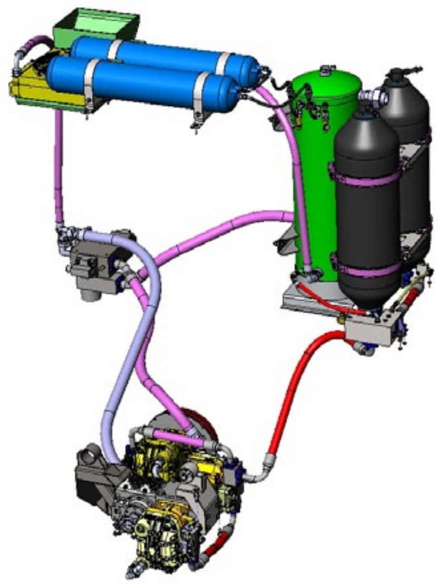
Figure 5-1 *Hybrid system components*



Analysis was completed that evaluated the performance differential between one 22-gallon high-pressure accumulator and two high pressure accumulators totaling 44 gallons. The analytical fuel economy results showed that the addition of a second accumulator yielded a 4–11 percent improvement over a single accumulator system, depending on the duty cycle. These improvements outweighed the cost and weight of the additional components and added complexity of the system and were integrated into the bus.

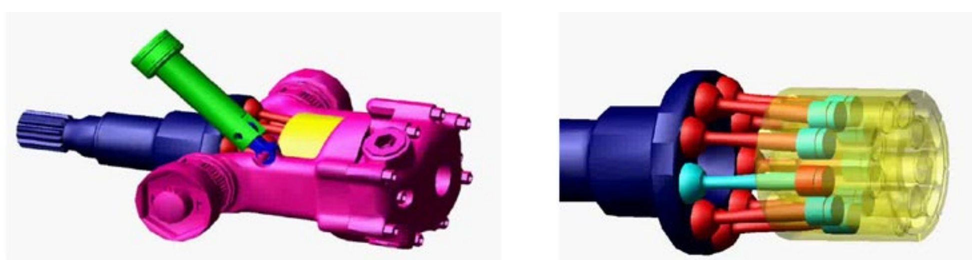
A large-capacity low-pressure reservoir (LPR) was not available to package in the space available. Therefore, a custom LPR was designed and manufactured. This design required additional overhead air capacity. To supply this, two low profile air tanks were added to the system. These tanks are shown in blue in Figure 5-2. The custom-designed LPR is shown in green.

Figure 5-2
Hybrid subsystem



Prior research was done to select the optimal variable displacement pump design. Two main designs are used, the swash plate pump and bent axis pump. The bent axis pump has the best efficiency of the two and was selected to be used. This is a piston pump design containing multiple axial pistons mounted at an angle to the drive shaft. An example of a bent axis pump is shown in Figure 5-3. This design is integrated into the Parker pump/motor offerings.

Figure 5-3
Example of bent axis pump



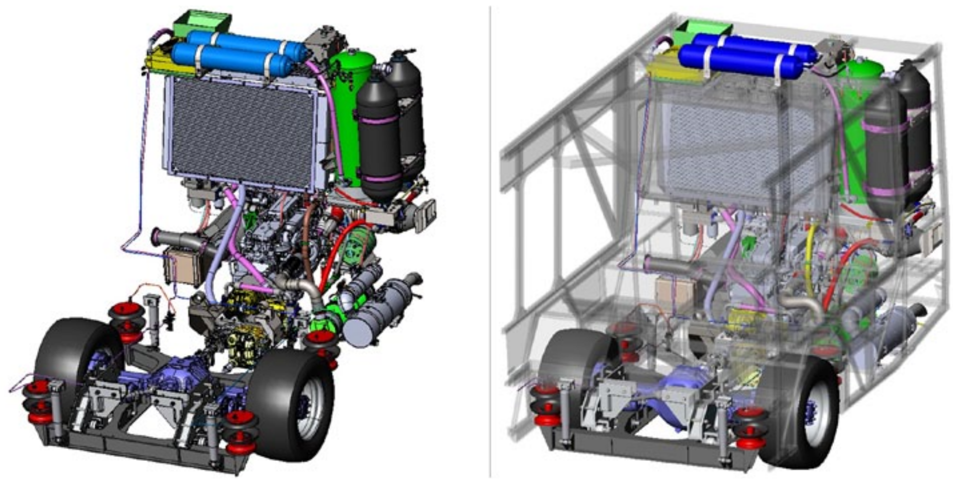
Vehicle Integration

Once the system was designed and analyzed, it needed to be integrated into the vehicle. This was done carefully to allow easy access to components requiring routine maintenance. The low-pressure manifold containing the hydraulic fluid filter and high-pressure accumulators containing replaceable bladders were the two components requiring easy access. The filter was placed just inside the right rear door, and the accumulators were designed with removable cross members to assist in removal for maintenance.

The most significant challenge for integrating the system was hydraulic hose routing. Due to high pressure and flow requirements, sizable rigid hoses were used. Attachment points on all hoses were critical, so as to not induce unwanted structure-borne noise. A carefully-engineered engine compartment enabled multiple hoses with large radii to be elegantly packaged. The full system, integrated with adjacent subsystems, is shown in Figure 5-4.

Figure 5-4

Hybrid system integrated in bus

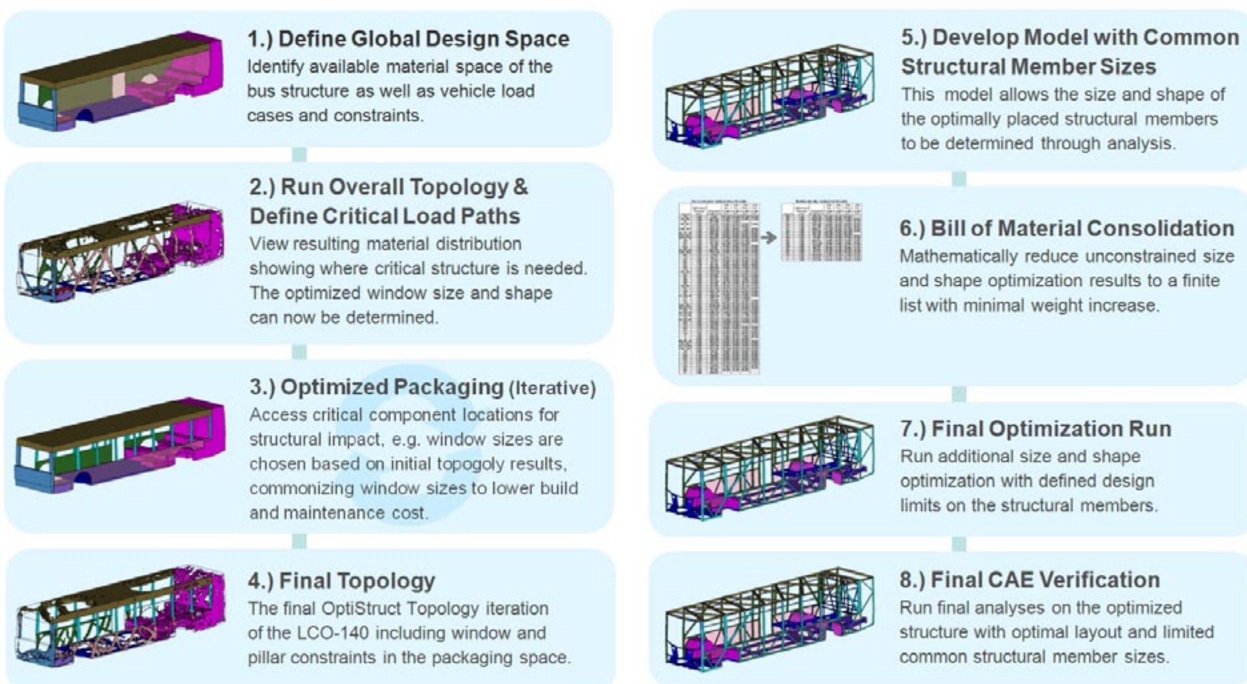


SECTION
6

Optimized Aluminum Structure

Altair's topology optimization tools define the optimal load paths in a given design space. This minimizes mass by putting members in the best place. Each member goes through size and shape optimization to minimize wall thickness and tailor the cross section to the structural need. This process yields the lightest practical structure possible for that defined application. A pictorial of this process is shown in Figure 6-1.

Figure 6-1 *Altair optimization design process*



Material Selection

Although the topology optimization of the bus structure does not take into consideration material properties, intelligent application of the structure optimization does require a selected material. Early in the program, a high-strength stainless steel was selected as the primary structure material. This was chosen mainly because of its common nature in the industry, above-average corrosion resistance, and post-welded strength. As the program progressed, the availability of off-the-shelf high-strength stainless steels was found to be scarce, specifically in the sizes required to fabricate the optimized bus structure. Further investigation found that the cost to roll-form the necessary sections for prototype volumes was prohibitive to the program. At this time, other material solutions were investigated.

Aluminum, weighing one-third that of steel, was initially investigated because it contributes to the "green" image for the transit bus structure application. It is 100 percent recyclable, regardless of how many times it is melted down and reformed. This makes aluminum an ideal "green" metal. Upon further research, many other properties of aluminum made it an attractive material for the bus structure, the first being its availability and price point for prototype extrusions, and another being the additional functions that could be integrated into custom extrusion designs. Aluminum, specifically in the 6000 series alloys, has moderately high strength and has excellent corrosion resistance when not in direct contact with dissimilar metals. Because the bus structure was an all-aluminum design, the corrosion properties fit the application well.

Multiple alloys were reviewed, and 6061 with a T6 temper was selected. It is commonly used in various structural, building, marine, automotive, aerospace, and process-equipment applications. It has a typical yield strength of 40,000 psi and an ultimate tensile strength of 45,000 psi.

Joining Techniques

Upon selecting Aluminum 6061, a short exercise was performed to gain knowledge and understand the best way to join the sections of the structure. Some of the methods researched were conventional MIG and TIG welding, friction stir welding, structural adhesives, mechanical fasteners, extrusion connection design, and various combinations of the aforementioned joining techniques. For each of these joining methods, structural performance, ease and cost of manufacturing, and corrosion attributes were compiled and compared.

Mechanical joints were found to require fasteners made of aluminum, stainless steel, or galvanized steel to avoid the galvanic corrosion from adjoining dissimilar metals. Due to this, mechanical joints were minimized from the core structure, only appearing on cross-members that were required to be removed during the installation process. Attachments of adjacent components to the structure are prevalent throughout, and appropriate fasteners are used in these applications to minimize the potential for corrosion.

Subsequent meetings were scheduled with experts in multiple disciplines, including the Edison Welding Institute, top specialty welding companies, and aluminum extruders. Visual brainstorming sessions were conducted with these experts to focus on the specific applications on the bus. The data acquired during this preliminary research were used to exploit the benefits of aluminum. Multiple custom extrusions were used on the bus as a result of this research.

After all identified options were evaluated, a hybrid of conventional welding, structural adhesive bonding, and custom extrusion connection design were chosen as the joining methods for the structure. This solution benefited the overall bus structure, given the available timing and resources, thus minimizing the disruption of program timing and goals. Future research may identify exotic joining solutions that add additional value to the structural design.

Custom Extrusions

Out of the 25 extrusions used in the fabrication of the bus structure, 12 of them were custom. The ability of aluminum to be custom-extruded into thin flanges, complex angles, and intricate shapes allows for fewer components to perform the required functions. Using one piece to perform multiple functions also eliminates potential joints, which reduces material, weight, and fabrication cost.

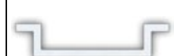
The cost for custom aluminum extrusions is relatively low. This is mostly due to the low cost of the extrusion die itself. In addition, the minimum volume of aluminum required per section is one billet. A billet is a cast block or bar of aluminum used to push through an extrusion die. Billets vary in size based on application (or circle size of the die extrusion) and are usually small and easy to handle. These cost details make aluminum an attractive solution for prototype and low-volume applications.

The 12 custom extrusions used for the structure are shown in Table 6-1. The remaining extrusions used were readily available from local metal suppliers and consisted of common geometric shapes and gauges used in multiple industries for various applications.

Table 6-1

Custom Extrusion Table

Custom Aluminum 6061-T6 Extrusions on LCO-140H

	Part Number	Description	Length Needed (ft)	Gauge (in)	Cross-sectional area (in^2)	Lb/Ft	Cross Section	Comments / Functions
1	INV129-ES-1001	Rocker	78.0	0.375	5.080	5.974		-Eliminates compound miter cuts for side wall members
2	INV129-ES-1002	Window Header w/ integrated egress hook	75.9	0.140	0.450	0.529		-Egress window header support -Includes integrated bead to achieve precise bond gap.
3	INV129-ES-1003	Corner of Roof Line	75.9	0.375	5.250	6.174		-Mounting Surface for Baltek Roof Panels -Eliminates compound miter cuts for side wall members
4	INV129-ES-1004	Belt Line	69.7	0.375	1.880	2.211		-Eliminates compound miter cuts for side wall members -Accepts interior shear panels with rider friendly closeout. -Includes integrated bead to achieve precise bond gap for shear panels.
5	INV129-ES-1005	A pillar	17.1	0.563	2.890	3.399		-Accommodates Exoskeleton Design. -Integrated windshield mounting surface.
6	INV129-ES-1006	Hat Section - Roof	111.8	0.142	1.630	1.917		-Mounting Surface for Baltek Roof Panels. -Includes integrated bead to assume precise bond gap.
7	INV129-ES-1007	Hat Section - Floor	28.7	0.313	1.450	1.705		-Mounting Surface for Baltek Roof Panels. -Includes integrated bead to achieve precise bond gap.
8	INV129-ES-1008	Rear Seat Support Hat Section	23.4	0.157	0.630	0.741		-Mounting surface for rear seats over unsupported wheel well
9	INV129-ES-1009	1.5" x 1.5" Square Tube	128.0	0.375	0.984	1.158		Aluminum 6061-T6
10	INV129-ES-1010	2" x 2" Square Tube	52.0	0.500	1.750	2.058		Aluminum 6061-T6
11	INV129-ES-1011	1.5" x 4" Rectangle Tube	109.0	0.250	1.313	1.544		Aluminum 6061-T6
12	INV129-ES-1012	2" x 4" Rectangle Tube	41.1	0.375	2.109	2.481		Aluminum 6061-T6

Integration of Functionality to Reduce Cost

One of the benefits of using aluminum for the structure is the ability to integrate functionality into custom extrusions. This extends the usefulness of the section beyond a simple structural support and allows it to perform multiple functions. These functions can add aesthetics to the overall look of the finished bus, as well as eliminate components by integrating additional solutions into the section. Fewer extrusions that perform more functions require less tooling to manufacture, fewer pieces to assemble, improve the dimensional accuracy of the resulting assembly, and overall reduce the cost of the structure.

The custom extruded A-pillar eliminates unnecessary material and bonding with the featured flange for the windshield to bond to. Had the flange not been integrated into the original extrusion design, a flange would have needed to be bonded to the A-pillar, which is an additional part and adhesive per side of the structure. Time, money, resources, and material were conserved with this particular extrusion.

The A-pillar extrusion also adds to the aesthetics of the bus. This section doubles as an exterior and interior finished surface. By using the structure itself as a surface, trim panels can be eliminated from the component list. This reduces cost, fabrication time, and weight. This also allows for styling freedom to give the bus a unique and eye catching look. A photo of this section is shown in Figure 6-2.

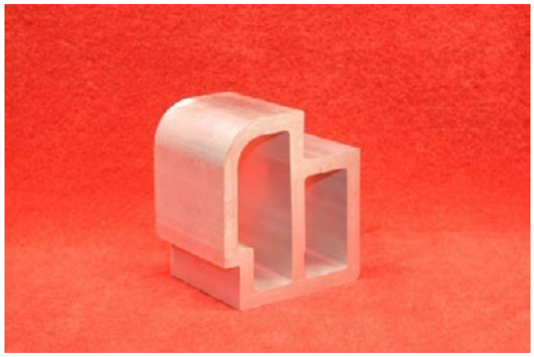
Figure 6-2

A-Pillar custom aluminum extrusion

Another section that adds aesthetics and has an integrated feature is the roofline structural members. These sections run the length of the bus, and in addition to the A-pillar, act as an exterior finished surface. These two sections together provide a unique feature that can be described as an exoskeleton design. Typically, vehicle structures are covered up at the cost of additional weight and manufacturing time. This application shows that with the right material and aesthetic design, the structure no longer needs to be hidden. The added feature in this section is the right-angle notch, which allows for a clean mounting strategy of the roof panels. This section is shown in Figure 6-3.

Figure 6-3

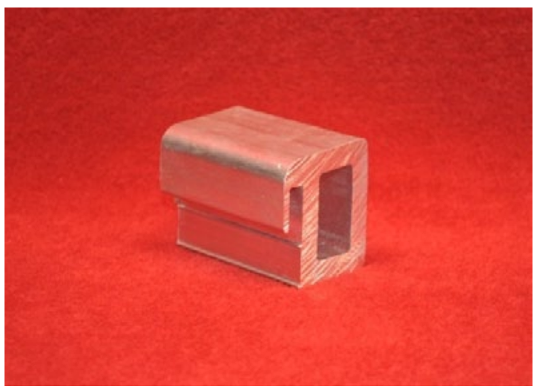
Roof Line custom aluminum extrusion



On the inside of the bus, the window sill showcases another application of the custom extrusion. This section primarily acts as the "belt line" structural support. It also has a smooth integrated lip that captures the interior aluminum sheer panels and gives a user friendly arm rest to the passengers. This section is shown in Figure 6-4.

Figure 6-4

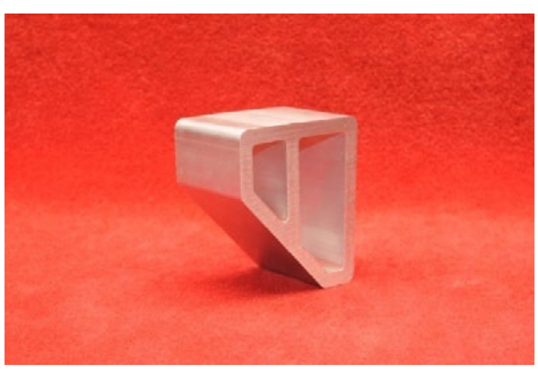
Belt Line custom aluminum extrusion



The side walls of most buses, as in most passenger cars, are slightly angled to manage large window reflections. This often leads to complex fixturing and angled cuts during the manufacturing process. In order to eliminate these angles during fabrication, the custom extrusions on the roof line, belt line, and floor line (or rocker) were extruded with custom angles already built into them. This eases the manufacturing process by reducing setup and fabrication time. These sections are shown in Figure 6-5.

Figure 6-5

Floor line custom aluminum extrusion



SECTION

7 Vehicle Build

Once the CAD design was complete and the CAE results verified, the component procurement process began. The initial focus was the structure. It was both fabricated and tested before the build moved forward. With the addition of the front and rear axles and suspensions, the bus rested on four tires and could be pushed around the build facility. The powertrain and controls were then installed in the bus, and the bus was transported to a dynamometer facility for initial startup and system commissioning. After the vehicle was verified to safely run at the dyno, the exterior was completed so that final powertrain system commissioning could take place at the proving ground. Last, the interior was completed for a show-ready demonstration vehicle.

Program funding varied greatly throughout the entire bus development process and even stalled at one point. Because of this, the vehicle build was completed in the discrete stages outlined in this chapter, as funding became available. This enabled continual progress with the least amount of disruption to the program or its success.

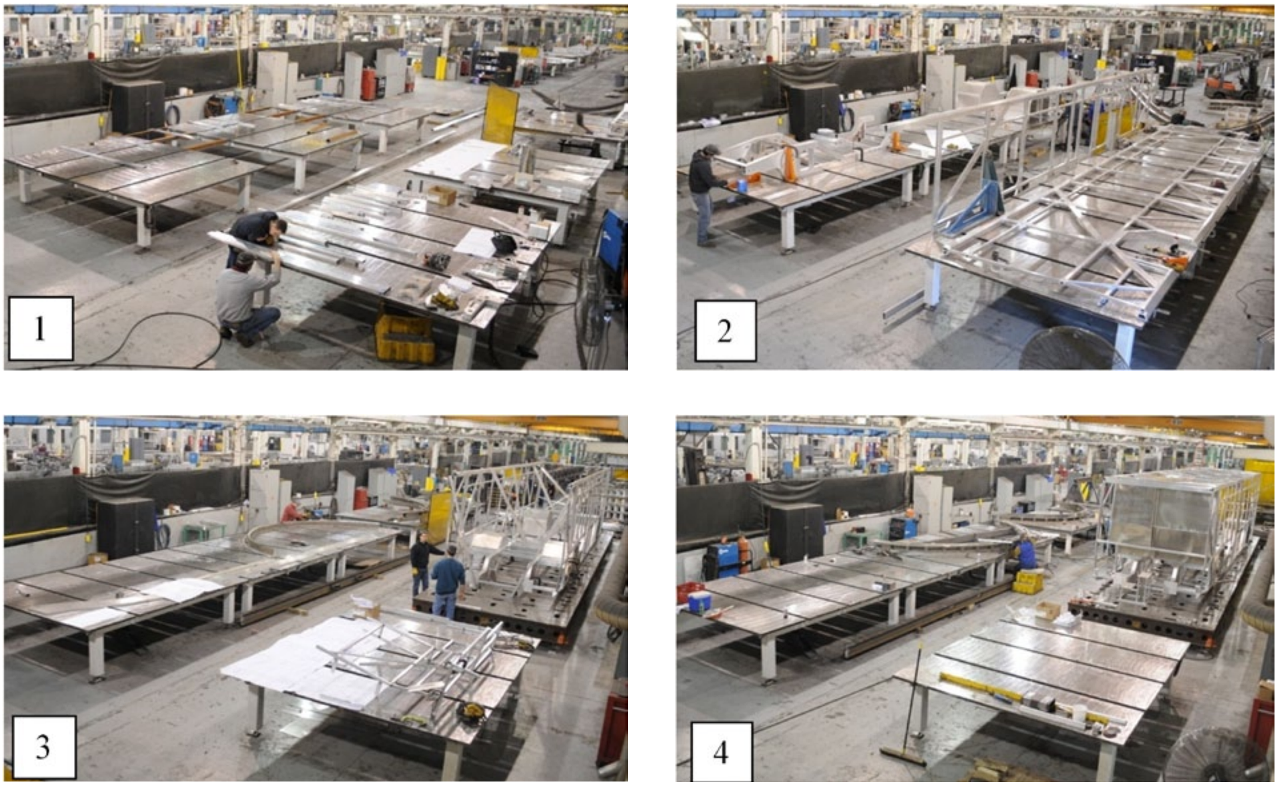
Component procurement was also affected by program funding. In some cases, additional build support was required to meet deadlines. When possible, local suppliers were engaged to assist with the required support. This not only benefited the build process by having vendors close by for occasional on-site visits, but also distributed the program funding to benefit the local economy.

Structure Build

Altair procured the necessary material to fabricate the all-aluminum structure in-house. In order to manage resource availability and timing constraints, Altair researched outside fabricators/assemblers that were qualified to assist with this large fabrication. After careful consideration of three qualified companies, Altair awarded the fabrication of the structure to Michigan-based Odyssey Industries on February 3, 2010. The completed bus structure was delivered to the Altair Engineering World HQ in Troy, Michigan, on April 9, 2010.

Odyssey dedicated a small area in its 160,000 sq. ft. facility to the Altair bus structure build. With a dedicated fabrication team with certified aluminum welders, the structure quickly took shape. Figure 7-1 shows a four-slide time lapse photo of the bus fabrication. First, the main sub-assemblies were laid out on precision ground bed plates. Second, the sub-assemblies were carefully TIG welded together and set aside. Third, the sub-assemblies were brought together. Fourth, the final attachment welds were completed and the vehicle structure was measured using a laser CMM machine to check for acceptable tolerances at critical interfaces.

Figure 7-1 *Time-lapsed aluminum structure build*



The bus structure was then weighed, shrink-wrapped, and transported to Altair for the next step in the build process. This completed a significant milestone in the program. Figure 7-2 shows the finished structure at Odyssey and in the Altair build facility where the remainder of the build would take place.

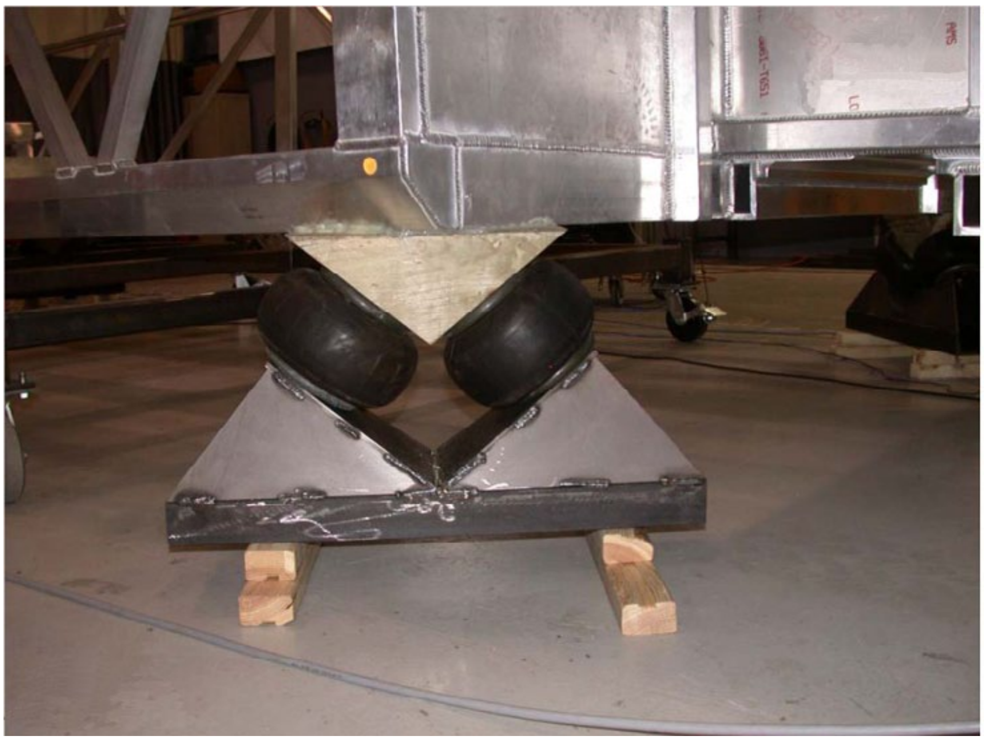
Figure 7-2 *Final bus structure relocated from Odyssey to Altair*

Structure Verification Testing

Before the bus build continued, Altair took opportunity to correlate the structure with the CAE analysis. A third-party testing company was secured to perform a modal test of the structure to identify the actual low frequency mode shapes.

The test was set up with eight rubber airbags supporting the bus at four locations to represent a "free-free" boundary condition. Each set of airbags was fixtured at a 90° angle and pressurized with low air pressure (~30 psi) to minimize interference on the modal testing. A picture of the airbag setup is shown in Figure 7-3.

Figure 7-3
Airbag setup



Excitation to the bus structure was provided with two electro-dynamic shakers. These shakers were set up with the bases rigidly mounted to the floor. The front shaker was positioned 15° from vertical in the lateral direction. The rear shaker was positioned 15° from vertical in the fore/aft direction. The combined orientation of these two shakers allowed for the effective excitation of the significant modes. A photo of these shakers is shown in Figure 7-4.

Triaxial accelerometers were attached to selected geometry points as close to the vehicle global coordinate system as possible. Over 100 selected data points were tested to represent an accurate model for correlation. A photo of the accelerometer attachment is shown in Figure 7-5 as is an image of the geometric points where the accelerometers were attached.

Figure 7-4
Shaker setup

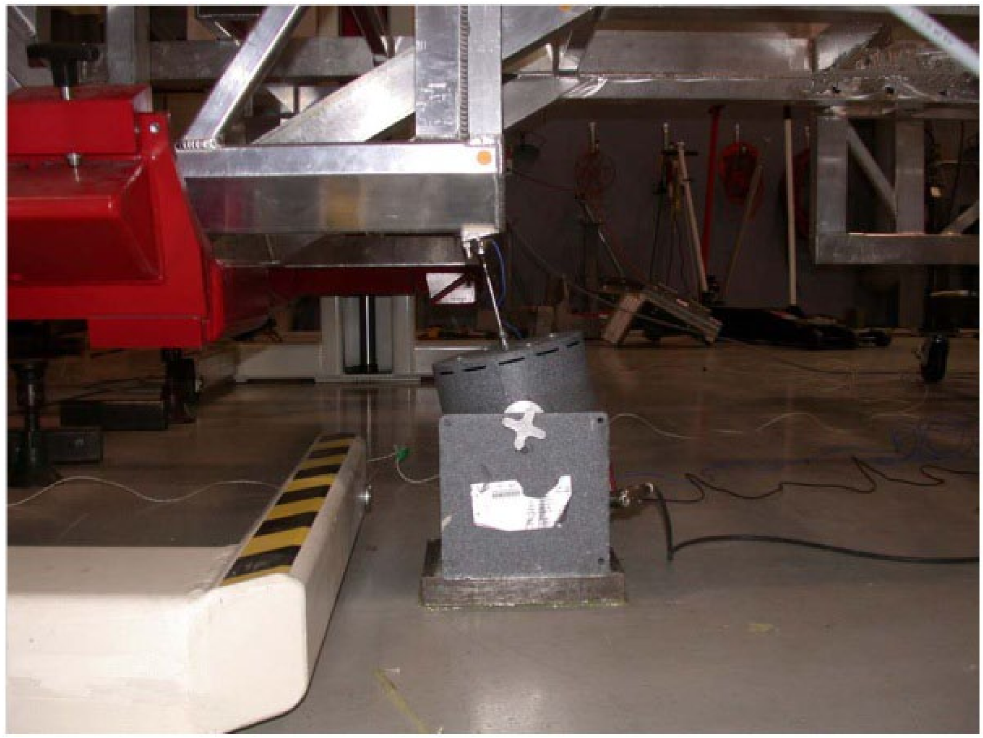
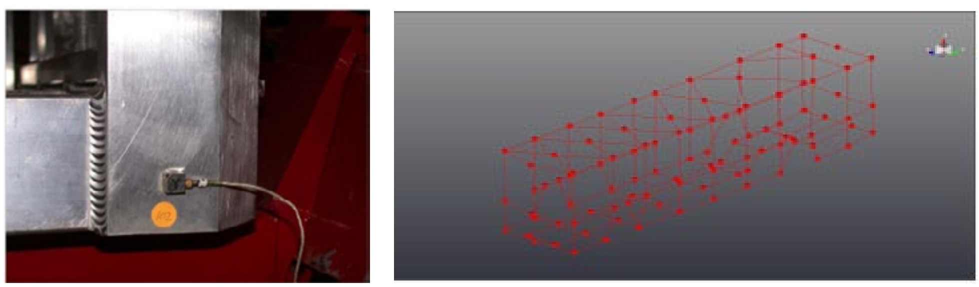


Figure 7-5
Accelerometer setup and geometric point locations



A total of 28 distinct mode shapes were documented from the modal testing. The first two modes identified in the CAE analysis were 13.4 and 13.8 Hz, respectively. The first two modes identified with the testing were 13.27 and 13.72 Hz, respectively. The first mode is best described as a front match box and the second as a first torsion, which was observed in both the analytical and physical test data. This exercise proved that the analytical model and physical bus structure correlated extremely well.

Figure 7-6
Modal testing of aluminum bus structure

Rolling Chassis

The next stage of the build was to install the suspension, steering, operator's station, and brakes. This provided a rolling demonstrator that could be moved throughout the build facility. A temporary floor was installed to easily move throughout the cabin during the build process. Side panels were bonded into place, and air tanks were installed to supply air to the suspension components requiring them. A photo of the rolling chassis is shown in Figure 7-7.

Figure 7-7
Rolling chassis

Dynamometer (Dyno) Ready

The population of the engine compartment was the next phase of the program. This involved the assembly of multiple subsystems. The entire powertrain was assembled. All system fluids were filled and a pre-startup inspection was performed. A photo of the completed engine compartment is shown in Figure 7-8.

Figure 7-8

Completed engine compartment

The bus was then transported to a dyno facility where the hybrid driveline system could be initially commissioned. The bus was positioned in a dyno cell, anchored to the floor, and then safely started. This initial commissioning was the first opportunity to test the controls methodology for proper function before taking the bus to a proving ground facility where it could be road-tested. Controls development was limited as regenerative braking could not be tested at this facility. This phase was completed when the vehicle safety checks were verified, and the vehicle successfully ran at a constant 40mph. A photo of the bus in the dyno facility is shown in Figure 7-9. FTA funding was fully expended at the completion of this phase.

Figure 7-9
Bus in dyno facility

Proving Ground Ready

With the program stalled due to a lack of funding, the Michigan Economic Development Corporation (MEDC) stepped in and assisted Altair in funding the program through the next stage. This stage entailed on-road driving and fuel economy testing at a proving ground. For this to occur, the vehicle needed to be closed in and watertight, as the testing phase would be conducted throughout the Michigan winter season. The front and side glazing were added along with safety systems such as bumpers, mirrors, windshield wipers, and lighting. Entrance/exit doors were added with side paneling and rear access doors. A photo of this bus is shown in Figure 7-10.

Figure 7-10
Enclosed bus ready for proving ground testing

Ready for Public Showing

After fuel economy results were collected, the program goals had been met. Altair wanted to gain public awareness of the bus to showcase the innovative solution that came from the public/private partnership involving FTA. Before the bus would be publicly showcased, Altair decided it should be upgraded with additional equipment to make it more suitable for onboard test rides and to provide a detailed, finished product look. To accomplish these upgrades, additional funding was required, and Altair senior management decided to self-fund this effort. The upgrades included the completion of the interior of the bus, flooring, seating, passenger interfaces, overhead lighting and route displays, roof mounted HVAC system and ducting, wheel chair ramp, actuating front entry door, and a driver side control panel with switches and actuators. The addition of a vinyl wrap was placed on the exterior of the bus to draw attention to the technology and benefits of the low cost of ownership offering. The interior of the bus is shown in Figure 7-11, and a photo of the finished bus is shown in Figure 7-12.

Figure 7-11
Interior of LCO-140H

Figure 7-12
Completed Altair bus

SECTION

8

Vehicle Commissioning and Fuel Economy Testing

The LCO-140 H was brought to the Michigan Proving Grounds in February 2011 for commissioning. Until this stage, the vehicle was never driven on roads under its own power. Therefore, the vehicle needed to first undergo shakedown exercises. Then, when it was deemed safe, the controls refinement of the hybrid system could begin. Once the controls refinement was complete, the vehicle was ready for its first round of fuel economy tests.

Vehicle Shakedown

Upon arrival at the proving grounds, the vehicle required a period of shakedown exercises to ensure the safety of the bus and the passengers onboard. Altair vehicle development specialists drove the vehicle over multiple ride roads on closed courses to make sure all systems were functioning as designed. Initial systems targeted for shakedown were the brakes, followed by the steering, suspension, and powertrain.

During the vehicle shakedown, the interior noise was noted as objectionable. This was expected, as the interior package of the bus was incomplete and no sound deadening materials had been added to the vehicle package yet. To ensure a more pleasant rider experience during the test phase, the bus was temporarily outfitted with NVH materials to bring the noise down to non-objectionable levels.

Further shakedown activities revealed that the brake feel needed to be tuned. This was not safety-related, but rather passenger comfort-related. The bus was loaded with ballast to GVW, and additional shakedown exercises were performed at this loaded condition. Although some additional tuning was recommended, the foundation of the bus was deemed solid and ready for the next stage of commissioning. A final torque audit was performed on all the suspension, steering, and driveline components to confirm that no fasteners had loosened up during the shakedown activities.

Controls Refinement

The hybrid system components were purchased from Parker. Parker has successfully integrated its system components in multiple vehicle platforms. Therefore, the controls development strategy was initially defined by the Parker engineering staff. In cooperative efforts, Altair and Parker engineers jointly worked together to follow the controls development process to refine the systems drivability and functionality for the bus itself.

Initial control system safety checks were verified before the controls refinement commenced. These checks included monitoring pressures and temperatures in the system so no damage would occur to the vehicle while different controls algorithms were experimented with. Controls refinement then began by focusing on drivability with the brake regeneration function off. Being a pure series hybrid, this essentially focused on the acceleration and constant-speed driving controls, while 100 percent of the braking was performed by the conventional foundation brakes. As the hybrid driveline analysis predicted, the system offered more startup torque than required. The main focus was to dial back the power the driver had to ensure a comfortable ride for standing passengers under acceleration.

The regenerative braking feature was then added to the controls package, and development began. The braking function cannot rely solely on the hybrid system. Proper blending of the hybrid regenerative brakes and the foundation brakes need to be developed to recapture as much energy during the braking event while allowing the driver to smoothly come to a comfortable stop. The one area where regenerative braking is not used at all is during emergency stops. Anytime the ABS is in use or the driver applies an extreme input to the brake pedal, the hybrid regenerative braking immediately cuts out and all stopping is managed strictly by the foundation brakes. This is, in large part, due to the need to adhere to FMVSS regulations. Safety is of the utmost importance.

Once the acceleration, constant speed, and braking controls were optimally functioning and delivering acceptable drivability, the engine-off strategy was installed. This involves more than merely cutting the engine off every time the bus stops; the controls package has to monitor the vehicle's vital functions to ensure that shutting down the engine will not negatively affect other systems. This includes air pressure monitoring, electrical voltage monitoring, and hydraulic pressure monitoring. It is critical that the engine shuts off only when all three of these systems are satisfied with their current state of charge.

The last stage of commissioning involved fuel economy performance. While, conceptually, this variable was considered throughout all of the controls development, it needed to be verified. The bus was driven over multiple duty cycles and fuel economy was observed. It was compared to vehicles in different classes over the same duty cycles with a similar hybrid system. Minor changes were made to the controls to see how they would affect the fuel economy performance. An optimal controls strategy was decided upon.

A Design Verification Plan (DVP) was completed to check the final controls strategy for function and safety. This concluded the commissioning, and the vehicle was ready for fuel economy testing and showcasing. A photo of the bus on the proving grounds during the commissioning phase is shown in Figure 8-1.

Figure 8-1

Bus commissioning at Michigan proving grounds

Fuel Economy

The goal of the fuel economy testing was to use duty cycles that could be replicated easily, yield high repeatability, and deliver results that could be compared to current industry buses. Those duty cycles that were considered were OCTA, Double Manhattan, Arterial, CBD, and Commuter. The OCTA and Double Manhattan duty cycles are good representations of real-world duty cycles but are challenging to replicate on the road with high repeatability. Further, there is a limited amount of OCTA and Double Manhattan duty cycle fuel economy data available for buses, and what is available is mostly analytical data. The Arterial, CBD, and Commuter duty cycles have been used as the standard for bus testing at FTA's Altoona Bus Testing and Research Center for well over 12 years. Because of this, there is documented fuel economy data on virtually every transit bus that is on the road today, available to the public through the Altoona Bus Testing and Research Center.

The Altoona Fuel Economy Test procedures were reviewed and deemed reasonable to replicate on the Michigan Proving Grounds in Romeo, Michigan. A suitable portion of the track system was identified and labeled with signage marking critical measured points on the route. The legend used for the track system signage colors is shown in Table 8-1. Signs had an A, B, or C printed on them to denote which duty cycle it was. Sign "A" stood for Arterial, sign "B" stood for Central Business District, sign, "C" stood for Commuter. A photo of signage on the track is shown in in Figure 8-2.

Table 8-1
Fuel Economy Track Signage Color Legend

Red	Stop/start from/acceleration
Blue	Target hit, maintain constant speed
Yellow	Begin deceleration

Figure 8-2
Fuel economy signage on test track

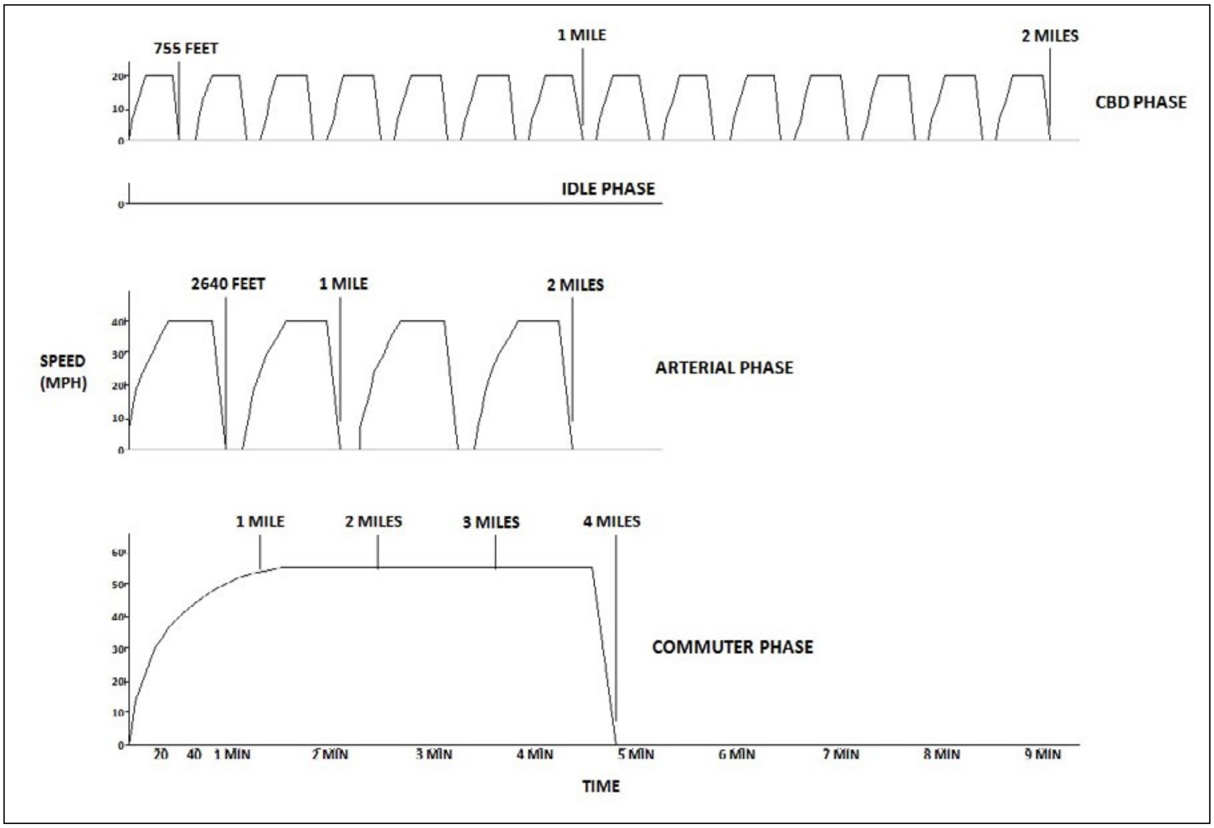
The Commuter, Arterial, and CBD are all individual duty cycles that make up the Design Operating Profile, as described in the Transit Coach Operating Duty Cycle (ADB Cycle) by the Altoona Bus Testing and Research Center. The test is performed at seated loaded weight using a procedure based on SAE standard 1376. The phases have varying numbers of speeds, miles, and number of stops. These details are defined in Table 8-2.

Table 8-2 *Design Operating Profile Duty Cycle Definition*

Phase	Stops/ Mile	Top Speed (mph)	Miles	Accel. Dist. (ft)	Accel. Time (s)	Cruise Dist. (ft)	Cruise Time (s)	Decel. Rate (fpsps)	Decel Dist. (ft)	Decel. Time (s)	Dwell Time (s)	Cycle Time (min s)	Total Stops
CBD	7	20	2	155	10	540	18.5	6.78	60	4.5	7	9-20	14
Idle	-	-	-	-	-	-	-	-	-	-	-	5-0	-
Arterial	2	40	2	1,035	29	1,350	22.5	6.78	255	9	7	4-30	4
CBD	7	20	2	166	10	510	18.5	6.78	60	4.5	7	9-20	14
Arterial	2	40	2	1,035	35	1,350	22.5	6.78	255	9	7	4-30	4
CBD	7	20	2	155	10	510	18.5	6.78	60	4.5	7	9-20	14
Commuter	1 stop for phase	Max. or 55	4	5,500	90	2 mi + 4,580 ft	188	6.78	480	12	20	5-10	1
Total			14									47-10	51

Average Speed = 17.8 mph

Figure 8-3 *Design operating profile–graphical view*



The Altoona Bus Testing and Research Center is careful to point out where it modifies the fuel economy test procedure as written. First, it eliminates the use of a control vehicle. Second, the test track at the facility is 238 feet short of 1 mile. This is acknowledged and essentially cuts testing cycles short by 238 feet. Therefore, the CBD and Arterial routes are 576 feet shorter than the published cycle, and the Commuter is 1152 feet shorter than the published cycle. The data collected by Altair was similarly modified by adjusting the cruise distance and time to reflect this change. Third, an electronic fuel measuring system was used to indicate the amount of fuel consumed during each phase of the test. Last, the acceleration portion of the duty cycle was always performed under a wide open throttle position. This is done by the Altoona Bus Testing and Research Center to increase repeatability of each test.

In addition to following the all Altoona Bus Testing and Research Center modifications, a change was made to the track. The Altoona Bus Testing and Research Center uses an oval track surface that is exactly 238 feet short of 1 mile. An identical loop was unavailable at the Michigan Proving Grounds. Therefore, the testing was performed on an east/west track system. Instead of running clockwise and counterclockwise on a loop to average out elevation and wind factors, the test was run east, then west, and then averaged out. This was felt to be a reasonable compromise to the loop method used at the Altoona Bus Testing and Research Center.

Fuel economy testing was performed, and the detailed results can be found in the Fuel Economy Summary Sheet in Figure 8-4. The overall average fuel consumption as calculated per the Altoona Bus Testing and Research Center test procedure was 6.9 MPG. These results exceeded the predictions of the conservative analytical model used to predict fuel economy.

Figure 8-4 *Fuel economy summary sheet*

FUEL ECONOMY SUMMARY SHEET

BUS MANUFACTURER	: Altair Product Design	BUS NUMBER	: 001
BUS MODEL	: LCO-140H	TEST DATE	May 31 - June 14, 2011

FUEL TYPE	: DIESEL - ASTM D2 (Summer Blend)
SP. GRAVITY	: 0.860
HEATING VALUE	: 131500 BTU/Lb
FUEL TEMPERATURE	: 60.00 deg F
STANDARD CONDITIONS	: 60 deg F and 14.7 psi
DENSITY OF WATER	: 8.3373 lb/gallon at 60 deg F

CYCLE	TOTAL FUEL USED (GAL)	TOTAL MILES	FUEL ECONOMY MPG (Measured)	FUEL ECONOMY MPG (Corrected)
Run # :1, NE				
CBD	0.786	5.72	7.279	7.263
ART	0.713	3.82	5.358	5.368
COM	0.423	3.80	8.984	8.941
TOTAL	1.921	13.335	6.941	6.933
Run # :2, SW				
CBD	0.777	5.72	7.361	7.349
ART	0.779	3.81	4.889	4.898
COM	0.412	3.79	9.197	9.153
TOTAL	1.968	13.32	6.767	6.760
Run # :3, NE				
CBD	0.781	5.72	7.329	7.317
ART	0.682	3.81	5.593	5.604
COM	0.426	3.79	8.909	8.816
TOTAL	1.889	13.33	7.059	7.045
Run # :4, SW				
CBD	0.797	5.72	7.176	7.172
ART	0.743	3.81	5.120	5.129
COM	0.412	3.79	9.213	9.121
TOTAL	1.952	13.32	6.822	6.814

IDLE CONSUMPTION (MEASURED) - *Engine Off*

First 20 Minutes Data:	0.0 GAL	Last 20 Minutes Data:	0.0 GAL
Average Idle Consumption:	0.0 GAL/Hr		

RUN CONSISTENCY: % Difference from overall average of total fuel used

Run 1 : 0.59 Run 2 : -1.85 Run 3 : 2.27 Run 4 : -1.01

SUMMARY (CORRECTED VALUES)

Average Idle Consumption	: 0.00 G/Hr
Average CBD Phase Consumption	: 7.275 MPG
Average Arterial Phase Consumption	: 5.250 MPG
Average Commuter Phase Consumption	: 9.008 MPG
Overall Average Fuel Consumption	: 6.888 MPG
Overall Average Fuel Consumption	: 52.40 Miles/Million BTU

SECTION
9

Vehicle Showcase

Upon the completion of the LCO-140H technology demonstrator, three events were set up and targeted to increase public awareness of the bus. The first was Sponsor Day to give a first look at the bus to the sponsors and partners that worked hand-in-hand with the program. Second, a Media Day and press conference were held to unveil the bus to the public by inviting selected guests and media to see the bus. Last, the 2011 APTA Expo showed the bus to the target industry at its largest convention worldwide.

Sponsor Day

Altair held a Sponsor Day on August 31, 2011, at the Michigan Proving Grounds in Romeo, Michigan. This event was set up to thank the partners and sponsors for their support in the program. It enabled the invitees an opportunity to get an advance look at the completed, fully operational LCO-140H. They heard the first BUSolutions performance reports and took a ride in the bus on the proving ground track system. The day was essentially a way to thank the people most intimate with the program. It was also an opportunity to field questions about the bus and prepare for the press conference that followed a week later. Hosting the event on a closed course enabled a complete unveiling of the bus without public viewing before the unveiling at the Media Day event. The goal was to build excitement for the program that would lead up to the Media Day event. A photo of the bus on Sponsor Day is shown in Figure 9-1.

Figure 9-1 *Bus at Sponsor Day*

Media Day

A press conference was held on September 7, 2011, at the Altair World Headquarters in Troy, Michigan. This event was set up to unveil the LCO-140H to the public. Over 11 media outlets committed to attending and covering the event. Representatives from local and national government were present, and seven speakers were asked to speak about the program, including:

- James Scapa, Chairman and Chief Executive Officer, Altair Engineering, Inc.
- Mike Heskitt, Chief Operating Officer, Altair ProductDesign, Inc.
- L. Brooks Patterson (represented at the event by Maureen Krauss), Oakland County Executive
- Martin Dober, Senior VP, Entrepreneurship and Innovation, Michigan Economic Development Corporation
- Walter Kulyk, Director, Office of Mobility Innovation, Federal Transit Administration
- Ken Rogers, Executive Director, Automation Alley
- Louise Shilling, Mayor, City of Troy

The event included numerous displays showcasing the innovative content of the bus. Key suppliers were on hand to talk about their contributions to the program and showcase how their latest technology was used on the bus. Maureen Krauss spoke on Mr. Patterson's behalf as the Economic Development and Community Affairs Director for Oakland County. The Media Day event concluded with exclusive bus rides around the city of Troy on the LCO-140H for attendees. A photo of speakers at the event is shown in Figure 9-2.

Figure 9-2

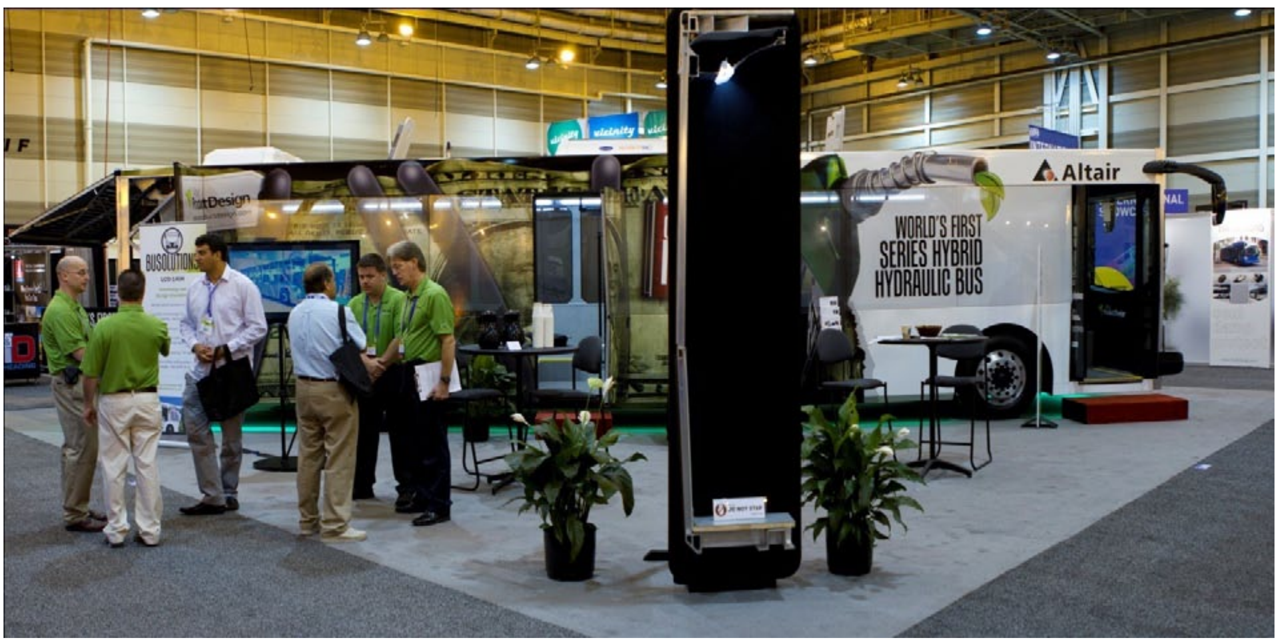
Speakers at Media Day

APTA Expo

The APTA Expo is the world's largest public transportation exhibition. It was held from October 3–5, 2011, in New Orleans. This Expo takes place once every three years and has nearly every public transportation product and service on display. The Expo expected more than 17,000 industry professionals to attend. This was the optimal public exhibition to showcase a new design for transit buses.

The LCO-140H was on display at the 2011 APTA EXPO; a photo is shown in Figure 9-3. Many industry suppliers, manufacturers, and transit authorities visited the booth to learn about the bus and its claims. The feedback from transit authorities was positive, with many requesting more information and inviting the bus to come to their cities for field trials. Universities and public resorts were also in attendance to learn more about the LCO-140H.

Figure 9-3 *Bus at APTA Expo*



SECTION 10

Results–Life Cycle Cost of Ownership

Life cycle cost of ownership is the estimated amount a transit authority will pay to own and operate a vehicle over its usable life. This does not take into account any revenue generated while it is in service. A standard heavy-duty transit bus found in most major cities across the United States has a 12-year life expectancy. In this timeframe, it is estimated to travel 500,000 miles. These are the design criteria for the bus, and the criteria used to compare the LCO-140H to the current buses available in the industry.

Purchase Price

The production vehicle cost of the LCO-140H is projected to be around $410,000. This is approximately $90,000 more than the cost of a conventional diesel bus. Part of this difference goes toward the cost of the hydraulic hybrid system. The remaining difference is in superior components that are either lighter weight than current industry standards or have a longer life, resulting in lower fuel and maintenance costs in the future. With the LCO-140H, the additional cost up front will yield savings that more than return that initial investment. When compared to a traditional diesel-electric hybrid bus, the upfront cost of the LCO-140H is about $121,000 less.

Fuel Costs

Fuel usage, next to purchase price, is the largest projected expense for any new bus. This is mainly because fuel prices continue to rise, but also because buses typically yield poor fuel economy. Under recent fuel price scenarios, fuel costs make up more than 50 percent of the cost of ownership on a conventional bus. Although fuel economy increases with Hybrid Electric offerings, the savings do not offset the additional cost of purchasing and maintaining the Hybrid Electric system. The fuel economy savings of the LCO-140H Series Hydraulic Hybrid are projected to more than offset the additional cost of purchasing and maintaining the system. Table 10-1 shows comparative examples of the overall average fuel economy performance of buses in service today compared to The LCO-140 & LCO-140H.

Table 10-1 *ADB Duty Cycle Fuel Economy Results of Buses Currently in Service*

BUSolutions LCO 140 Diesel (calculated)	Baseline Conventional Bus (average)	BUSolutions LCO 140H Hydraulic Hybrid (tested)	Gillig GM/Allison Hybrid Electric (2009)	New Flyer Hybrid Electric XDE40 (2010)
4.7mpg	3.3mpg	6.9mpg	4.74mpg*	5.34mpg*

*Data from Penn State Bus Testing and Research Center database

Scheduled and Unscheduled Maintenance

Scheduled maintenance, also called preventive maintenance, is typically performed in two intervals. The short interval maintenance consists of routine safety inspections, fluid checks, and component wear inspections. The purpose is to catch any problems before they become serious, preventing any out of service time. The long interval maintenance consists of in-depth inspections, fluid changes, and component changes. These include engine oil, transmission oil, fluid filters, brakes, etc. Any of these activities could be performed ahead of time if the short interval maintenance deems it necessary. Both maintenance activities take the bus out of service for a period of time and come with costs associated with parts and labor.

Reducing the time required by the service technician to complete scheduled maintenance events as well as reducing the time between maintenance intervals was a goal of the program. This was accomplished in many ways. Improving the access to routine maintenance items such as filters reduces the time and effort required to replace them. Reducing the need to replace components as often, such as the increased brake change interval due to the use of regenerative braking, reduces cost as well. These are very tangible goals that can be tracked to lifecycle costs.

Unscheduled maintenance occurs when parts fail prematurely or the vehicle is involved in an accident. Both events are unpredictable and cannot be directly tied into the lifecycle cost estimations. Efforts were made on the LCO-140H to reduce the frequency and duration of unscheduled maintenance. Having a favorable durability track record weighed heavily in the component/system selection process for the suppliers. Drivability for the operator was enhanced to reduce the likelihood of accidents. Although difficult to predict, the LCO-140H should lower unscheduled maintenance costs over the life of the bus.

Infrastructure Costs

Infrastructure costs such as employee training, alternative fuel or charging stations, depot modifications, and facility maintenance all add to the cost of ownership. A goal of the BUSolutions program was to eliminate, when possible, any additional infrastructure costs to current transit authorities. This is why the majority of core components came from the list of current industry suppliers.

The powertrain, although a hybrid, still has a diesel engine at its core. Provisions have been made to insert alternative fuel engines in the place of the diesel with little disruption to the system; however, the majority of transit authorities have existing diesel fuel tanks on their properties. The diesel engine results in a direct integration into existing TA infrastructures.

The other half of the powertrain has hydraulics at its core. Hydraulic systems are already used in conventional buses today and are understood by the maintenance personnel at transit authorities. This means that minimal employee training will be required for the adaptation of this technology.

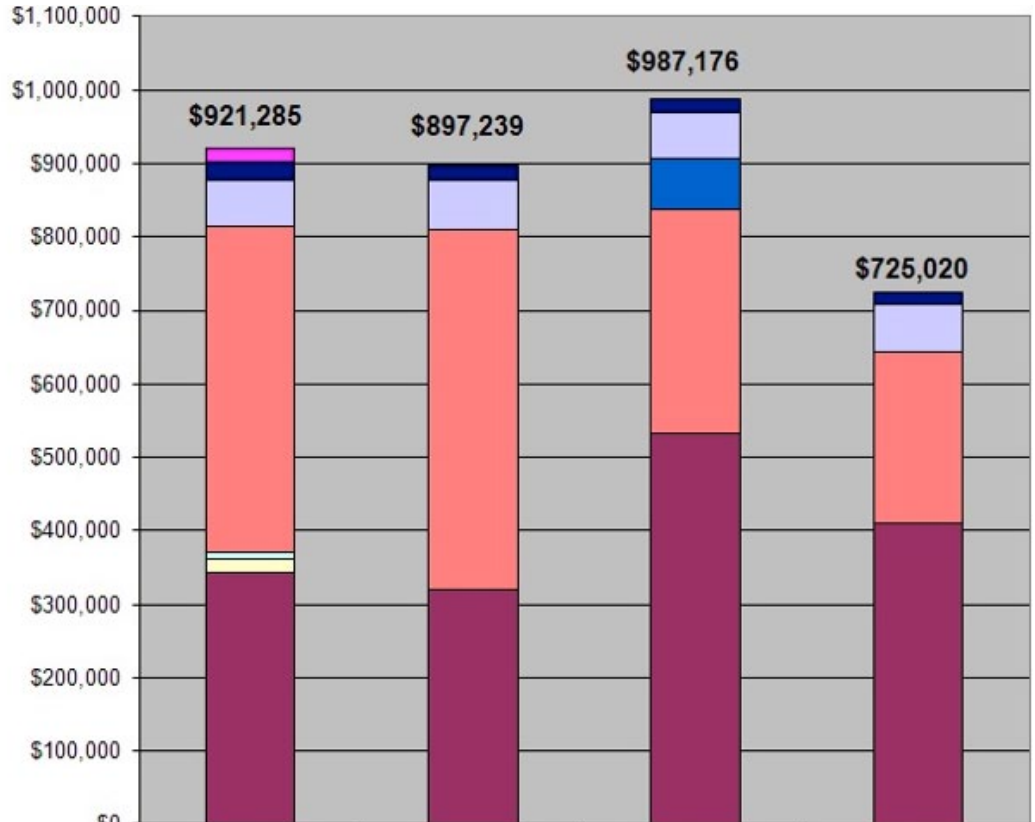
Cost Comparisons

There are many factors that need to be considered when comparing costs. Too often, procurement appointees focus on one or two of these factors when making a purchase. Looking at purchase price alone, a conventional diesel is the easy selection; however, the savings at the time of procurement will be quickly surpassed by the additional cost from fuel usage. Electric hybrids have improved fuel economy but have high purchase prices as well as maintenance costs that negate fuel savings.

The LCO-140H is the only hybrid option that reduces fuel usage and costs less than a conventional diesel to purchase, own, and operate over its lifecycle. To calculate the total cost of ownership comparison of the LCO-140H to other transit buses in the industry, Altair used the FTA report "Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation" (FTA-WV-26-7004.2007.1). This report contains the results of an exhaustive cost study comparing traditional diesel buses, Compressed Natural Gas buses, and electric hybrids. A few updates were made for the purposes of this comparison. First, the fuel cost data were updated to the Annual Energy Outlook 2010 report to have a better future fuel cost estimate. Next, in an effort to make the comparison fair to new product offerings, the Electric Hybrid fuel economy results were updated from the industry average of 18 percent found in the FTA report in 2007 to the BEST electric hybrid fuel economy improvement (60%) on record in the Altoona database. Last, the LCO-140H series hydraulic hybrid bus was added using the same assumptions in the report and actual cost information from the BUSolution program.

These comparative data are broken down in Figure 10-1. As shown, the LCO-140H has a 20 percent lower purchase price than most electric hybrids and saves over 30 percent in total lifecycle costs. What is even more compelling is that the LCO-140H will save 20 percent in lifecycle costs over a basic non-hybrid diesel bus. For the first time, transit authorities and municipalities can reduce their reliance on oil and save money while doing it. This is the type of socially and fiscally responsible solution the transit industry can benefit from.

Figure 10-1 *Lifecycle cost per bus*



	Compressed Natural Gas	Ultra Low Sulfur Diesel	Diesel Electric Hybrid	Diesel Hydraulic Hybrid
Compression Electricity	$19,003	$0	$0	$0
Facility Maintenance	$24,433	$20,723	$17,470	$17,470
Propulsion-related Maintenance	$62,588	$66,394	$63,589	$63,589
Battery or Bladder replacement	$0	$0	$67,500	$0
Fuel Costs	$444,145	$488,979	$305,612	$233,961
Emmissions Equipment	$0	$1,434	$0	$0
Depot Modification	$8,750	$0	$1,400	$0
Refueling station	$20,000	$0	$0	$0
Vehicle Cost	$342,366	$319,709	$531,605	$410,000

Data source: Transit Bus Life Cycle Cost and Year 2007 Emissions Estimation (FTA-WV-26-7004.2007.1).
Fuel cost data updated to the Annual Energy Outlook 2010 report.
Electric hybrid fuel economy updated to recent best-in-class 60% improvement for a fair comparison.
Delta cost estimates made for hybrid hydraulic with similar assumptions.

SECTION 11

Conclusions, Recommendations, Future Research

Conclusions

This report has documented the results of the BUSolutions program. This program is an example of a public-private partnership that truly worked. The results point to a product that could revolutionize the transit industry in a socially- and fiscally-responsible way.

The innovative design of the LCO-140H shows the benefits that can be gained by a simulation-driven design process when applied to a clean sheet design of a transit bus. The subsequent build and test of the demonstrator has proven the results of a series hydraulic hybrid transit bus that more than doubles the fuel economy seen in the basic diesel buses today. With an average 6.9 MPG as tested using the Altoona test procedures; this is 110 percent above the 3.3 MPG average fuel economy seen in diesel buses tested the same way. It is also 30 percent higher than the best electric hybrid in the Altoona database.

However, this was not done at an elevated cost to the transit industry. As shown, the LCO-140H has a 20 percent lower purchase price than most electric hybrids and saves over 30 percent in total lifecycle costs. What is even more compelling is that the LCO-140H will save 20 percent in lifecycle costs over a basic non-hybrid diesel bus. For the first time, transit authorities and municipalities can reduce their reliance on oil and save money while doing it. This is the type of socially- and fiscally-responsible solution the transit industry needs.

Commercialization Plan

Both FTA and Altair are motivated to move this program into a commercial phase. FTA desires to see the industry benefit from the introduction of a product developed with public investment that provides the benefits described above. Altair wishes to participate in a commercial venture to bring the LCO-140H to market and is discussing options with potential partners.

Future Research

In parallel with the pursuit of a commercialization plan, several continuing activities are recommended that will further validate and focus this concept for the needs to the transit industry.

Field Trials

While many TAs have been involved with the program in advisory roles, it is recommended that some field trials be run to get more tactical feedback on the bus operation and suitability for selected urban locales. Without putting the bus into revenue service, shadow trials could be run to make direct comparisons to selected buses and obtain feedback from a panel of riders and drivers. The results will help to identify other improvements to the design, help grow the user community awareness and acceptance, and add to the fuel economy validation on specific selected routes.

Altoona Fuel Economy Testing

Even though Altair endeavored to replicate the Altoona Fuel Economy Test as closely as feasible at the Michigan Proving Grounds, the verification of those results by a third-party test at the Altoona Bus Testing and Research Center would have value to dispel any doubts of the validity and repeatability of the fuel economy results.

Further testing could be considered, leading up to the full Altoona validation test suite before production ramp up.

Emissions Testing

With the drastic reduction in the fuel used and the ability to run the engine at more efficient points in the efficiency map, it is expected that emissions from the LCO-140H will be drastically reduced compared to a standard diesel bus. It would be useful to quantify this with emission testing at the Altoona Bus Testing and Research Center and perhaps jointly with the EPA Research Laboratories where a vast knowledge and experience with hydraulic hybrids resides.

Altair ProductDesign
The Shortest Distance Between Concept and Reality

BUSolutions LCO 140 Engineering Specification Sheet

	LCO 140H (Hybrid)
Overall Dimensions	
Wheel Base	275" [6,985mm]
Length	456"
Overall Length	466"
Width	102"
Roof Height	112.5"
Overall Height	124.5"
Front Overhang	84"
Rear Overhang	100"
Front Door Width	40"
Rear Door Width	34"
Rear Aisle Width	47"
Headroom Front axle	93"
Headroom Rear axle	78"
Floor Height	15.25"
Step Height	14"

Weight	**LBS**
Max GVW	40,500
Seat Loaded Weight (SLW)	31,950
Max Payload	14,700
Front GAWR	14,600
Rear GAWR	28,660
Total Base Curb Weight	25,800
Weight Distribution @ Curb (Front/Rear)	29/71
Note: RGAWR with super single tires is 24,000)	

Passengers	
Total Seats (including Driver)	41
Total Seats (including Driver and optional front wheel well seats	44
Wheel Chair locations	2
Standing Capacity	57

Powertrain	
Engine	Cummins ISB 6.7L I6 Turbo
Max HP	200-280
Max TQ	520-800 lb-ft @ 1600-1800
Transmission	Removed

	LCO 140H (Hybrid)
Axles	
Front Axle	Arvin Meritor - FH946U
Rear Axle	Arvin Meritor - AM71000
Axle Ratio	6.14:1

Brakes	
Front/Rear Disc	Meritor EX225H6
Anti-Lock System	MeritorWabco

Electrical	
Alternator	20 kW Hamilton Sundstrand (9050203-20-1)
Battery	Deka Group 31

Exhaust System	
Type	Fleetguard D56 2007 spec.

Fuel Tank	
Location/Capacity	Right Rear / 90 Gallons

Steering	
Type	RH Sheppard Closed Center Valve Gear

Tires	
Type (Front / Rear)	Michelin XZU2 / Michelin X-One
Size (Front / Rear)	275/70R22.5 / 455/45R22.5
SLR (Front / Rear)	17.7 in / 17.8 in
Weight (Front / Rear)	118.2 lbs / 202.9 lbs
Max Load (Front / Rear)	6940lbs @ 130psi / 11,700lbs @ 130psi

Wheels	
Type	Alcoa - Forged Aluminum
Size (Front-Rear)	22.5"x8.25" - 22.5"x15"

GLOSSARY

ADB Cycle (Advanced Design Bus Cycle): A transient cycle used to characterize bus operations in typical traffic situations. The cycle lasts about 47 minutes for a total travel of 22.5 km and consists of three phases: a Central Business District phase, an Arterial phase, and a Commuter phase.

APTA (American Public Transportation Association): A non-profit organization that serves as an advocate for the advancement of public transportation programs and initiatives in the United States. APTA is engaged in the areas of bus, paratransit, light rail, commuter rail, subways, waterborne passenger services, and high-speed rail.

ALTOONA: Altoona Bus Research and Testing Center based in Altoona, Pennsylvania. This center facilitates the testing that is required on all new model buses before they can be purchased with FTA funds.

BOM (Bill of Materials): A list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, components, parts and the quantities of each needed to manufacture an end product.

CAD (Computer Aided Design): The use of computer technology for the process of design and design-documentation.

CAE (Computer Aided Engineering): The broad use of computer software to aid in engineering tasks. Used to design, analyze, and manufacture products and processes.

CBD (Central Business District): Central district of a city generally located near the geographic heart of the city. Also, a bus fuel economy test cycle designed to simulate operation in a central business district.

Curb Weight: Weight of vehicle, including maximum fuel, oil and coolant; and all equipment required for operation and required by the APTA White Book Specification, but without passengers or driver.

DDM (Design Decision Matrix): A quantitative technique used to rank the multi-dimensional characteristics of an option set and is used in engineering for making design decisions. Uses an established set of criteria upon which the potential options can be scored.

DFMEA (Design Failure Mode Effects Analysis): An analysis method used in engineering to document and explore ways that a product design might fail in real-world use. DFMEA documents the key functions of a design, the primary potential failure modes relative to each function and the potential causes of each failure mode.

DVP (Design Verification Plan): Documents the strategy that will be used to verify and ensure that the product or system meets its design specifications and other requirements and is typically derived from the DFMEA process.

FMVSS: Federal Motor Vehicle Safety Standards promulgated by the National Highway Traffic Safety Administration at 49 CFR Part 571.

FTA: Federal Transit Administration.

GVW (Gross Vehicle Weight): Curb weight plus gross load.

GVWR (Gross Vehicle Weight Rating): The maximum total weight as determined by the vehicle manufacturer, at which the vehicle can be safely and reliably operated for its intended purpose.

Hybrid: A vehicle that uses two or more distinct power sources to propel the vehicle, with at least one of the power sources capable of reversibly storing energy.

Low-Floor Bus: A bus that, between at least the front (entrance) and rear (exit) doors, has a floor sufficiently low and level so as to remove the need for steps in the aisle between the doors and in the vicinity of these doors, enabling improved ingress/egress and wheel chair accessibility.

LPR (Low Pressure Reservoir): Acts as the supply and return reservoir for hydraulic fluid in a hydraulic system. Hydraulic fluid is taken from the LPR and is pressurized and stored in high pressure accumulators and then bled back into the LPR after flowing through the hydraulic motor.

MEDC: Michigan Economic Development Corporation.

Power Density: Power divided by mass, volume, or area.

Regenerative Braking: An energy recovery mechanism that slows a vehicle or object down by converting its kinetic energy into another form, which can be either used immediately or stored until needed. Used in a hydraulic hybrid system to convert kinetic energy into hydraulic pressure through the use of a hydraulic pump.

Seated Load: 150 lbs for every designed passenger seating position and for the driver.

SLW (Seated Load Weight): Curb weight plus a full load of seated passengers.

OCTA (Orange County Transportation Authority): A multi-modal transportation agency serving Orange County, California. Also, a bus fuel economy test cycle designed to simulate operation on routes served by OCTA; these routes are generally considered representative of routes at a number of other transit agencies.

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