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TP 14240E

# Development of a Multi-Mode Hybrid Electric Bus

Prepared for
Transportation Development Centre
of
Transport Canada

by
Overland Custom Coach Inc.

April 2004

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# Development of a Multi-Mode Hybrid Electric Bus

by
M.J. Shemmans, BET Services Inc.
and
C. Bland, BET Services Inc.
for
Overland Custom Coach Inc.

April 2004

*Since the accepted measures in the transit industry are both metric and imperial, metric measures and imperial measures are used in this report.*

*Un sommaire français se trouve avant la table des matières.*

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16. Abstract

The purpose of this project was to develop a multi-mode, energy-efficient, low floor, 28 ft. battery and hybrid electric bus for evaluation in an airport shuttle application and some specialized transit applications. A multi-phase approach was used, beginning with a feasibility study, followed by the systems design and building of a prototype, and ending with prototype proving tests. The prototype vehicle used a Siemens high-voltage drive system, featured an on-board high-power charging system, and was powered by ZEBRA batteries in conjunction with a Ford gasoline engine. The results validated the multi-mode approach, with a zero emission driving range in excess of 60 km or 37 mi. The design that was developed can be applied to create a practical low or zero emission shuttle that meets real-world applications.

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16. Résumé

Ce projet avait pour objet la mise au point d'un autobus à plancher surbaissé de 28 pieds à propulsion multi-mode (électrique et hybride-électrique) haut rendement, en vue d'une évaluation du véhicule comme navette aéroportuaire et sur des circuits de transport en commun spéciaux. La mise en œuvre du projet a comporté quatre phases : étude de faisabilité, conception des systèmes, construction d'un prototype et essais de validation du prototype. Le véhicule prototype était équipé d'un système d'entraînement Siemens haute tension, d'un appareillage de recharge rapide embarqué, de batteries ZEBRA et d'un moteur à combustion interne Ford. Les essais ont mené à la validation du concept multi-mode, et ont révélé une autonomie de plus de 60 km (37 mi) du prototype, dans la configuration zéro émission. Ils permettent d'envisager la mise au point de navettes à émissions faibles ou nulles, conformes aux exigences du monde réel.

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# EXECUTIVE SUMMARY

This project was initiated in response to appeals from transit and fleet operators as well as government agencies to reduce the emissions and fuel consumption of medium-duty vehicles while still providing practical range and performance. While diesel-powered vehicles work well in most transit, paratransit, and airport shuttle applications, the emissions from such vehicles may be linked to the poor condition of local air and the broader concern of global warming. Other electric or hybrid electric vehicles for shuttle duty have been recently developed that work well under restricted operating conditions, but these often do not have the range or performance required for more practical operation.

Overland Custom Coach (OCC) has experience in providing low-volume, custom-designed, low floor vehicles to the transit and paratransit industry. BET Services Inc. has extensive experience in development of traction battery systems, including development of the hardware and software required for the control and testing of battery systems. Siemens is a world-class supplier of electrical and electronic components and major electric traction systems. A practical hybrid electric shuttle bus was viewed as a realizable project based on a project team formed by these three companies. Having selected Siemens as the manufacturer of the drivetrain components and high-level control software, and OCC as the provider of the technology to develop a low floor vehicle, BET Services selected ZEBRA batteries, manufactured by MES-DEA, as the most promising battery technology for the development of the prototype multi-mode hybrid electric bus for shuttle service application.

The objective of the project was to develop an energy-efficient, low floor, 28 ft. hybrid electric bus for evaluation in an airport shuttle application and some specialized transit applications. The vehicle would have the capability of operating in battery-only drive, engine-only drive, and a range of hybrid electric drive strategies. This was termed the “multi-mode” drive concept.

Ultimately, a prototype 28 ft. hybrid electric shuttle bus was built capable of multi-mode operation. Testing was performed in both in the laboratory and under simulated in-service conditions at the sub-system, system, and vehicle level. Operation of the shuttle bus validated the feasibility of the multi-mode concept and has been used to demonstrate the possibilities of zero and/or reduced emission transit and airport shuttle applications.

The bus body and chassis for the prototype vehicle were pre-selected based on an existing base vehicle structure already developed by OCC: a well-proven, diesel-powered, low floor, 28 ft. shuttle that used the OCC Economical Low Floor (ELF) technology. Using its background in batteries for electric vehicles, BET chose to combine three 17.8 kWh, high-energy ZEBRA batteries with the Siemens drivetrain to create the hybrid powertrain. The batteries are high-temperature sodium/metal chloride chemistry designed specifically for use in electric and hybrid vehicles. They are parallel-connected, self-contained, high-voltage units, complete with thermal and electronic management systems. A Siemens drive system with a single 120 kW (peak) traction motor was integrated with the three ZEBRA batteries and a Ford 5.4 litre V8 gasoline/natural gas engine coupled to a Siemens 150 kW (peak) generator. For size and weight reasons the nominal voltage of the drive system chosen was near 600 V. Therefore, the ZEBRA battery system chosen for the bus had a nominal voltage in the region of 550 V.

The design studies had indicated that the hybrid powertrain could be packaged in the standard vehicle. With only slight modifications to the exhaust piping and related components, all of the internal combustion (IC) engine and electric drive components fit within the powertrain area of the base vehicle. The engine and electrical generator were mounted in the normal engine position and the traction motor and reducer were mounted in the area normally occupied by the transmission. The three ZEBRA batteries were mounted under the seats inside the bus. The inverters were also mounted inside the bus behind the driver's compartment, away from the major crash zones. Three 5.1 kW (15,000 BTU) heat pumps for vehicle climate control were mounted on the roof. The heat pumps operate from a 110 V AC on-board auxiliary inverter system.

By modest upgrading of just the rear tires, the GVWR (gross vehicle weight rating) of the vehicle was raised from the base of 7,255 kg (16,000 lb.) to 8,617 kg (19,000 lb.). No changes were made to the wheels to accommodate these tires. All other major design specifications of the hybridized vehicle remained the same as the base vehicle.

The architecture of the powertrain used in the prototype allowed the traction motor to receive its energy from the batteries (battery-only mode), from the engine via a generator (engine/generator-only mode), or from a combination of the two (hybrid electric mode). In hybrid mode the source of energy and power is shared according to the operating mode or strategy. In the prototype vehicle, an on-board computer is available to select the operating mode and program the mode parameters.

The engine is not mechanically connected to the drive wheels, and the accelerator pedal is not mechanically connected to the throttle of the engine. Instead, the on-board control system determines the required speed of the engine/generator combination, and all power is delivered electrically to the traction motor. In the prototype vehicle the reaction time of the Ford gasoline engine to speed request signals was not controlled to the extent hoped. Therefore, the engine/generator-only mode of operation was not implemented in this project.

When the vehicle brakes with or without the engine running, the energy flow is reversed allowing the battery to capture the regenerative braking energy.

The traditional approach for auxiliary control in buses is to mechanically drive the auxiliaries either directly from the engine or from a large auxiliaries motor electrically powered from the main high-voltage supply. Instead, the prototype bus incorporated an auxiliaries system in which one half of a 70 kVA, air-cooled, "duo" inverter was used to provide AC to power the auxiliary units including the 12 V systems. The other half of the "duo" inverter was used for on-board high-power charging. This allowed an electro-hydraulic pump for the power steering and power brakes, the three roof-mounted heat pumps, and the air compressor for the rear suspension to operate off a 110 V AC supply and be totally electrically driven, allowing them to be smaller, lighter, more efficient, and available in high volumes. The 12 V electrical system supplied from the original equipment manufacturer (OEM) was not altered from the base vehicle.

The OCC multi-mode demonstration vehicle has two different charging systems placed on board the bus:

1. For slow or overnight charging, the system used comprises three individual 3.2 kW chargers, one for each battery. These chargers require off-board connection to a 240 V AC supply.
2. For fast or interim high-power charging from the grid, the system used consists of one half of the air-cooled duo inverter. Since the ZEBRA batteries have a nominal voltage near 550 V DC, charging voltages can approach 700 V DC. By placing the high-power (high DC voltage) charger on board, the connection of the off-board (possibly outdoor) charging infrastructure can be made with lower and safer AC voltage connections. The off-board infrastructure for fast charge of the OCC shuttle can thus be implemented with relatively simple and inexpensive equipment.

A test bench using a motor shaft dynamometer was assembled at BET Services that enabled part and full powertrain systems of the prototype shuttle to be tested prior to road testing. The main purpose of the test rig was to prove out the various powertrain systems as well as various operating modes and hybrid strategies.

The duty cycle that was chosen for the focus of the design studies and bench test program was the Central Business District (CBD) + Arterial cycle. The CBD simulation that was used required accelerations from rest to 32 km/h and to 64 km/h at 0% grade. Performance was also examined for a route established in Quebec City, called the “ÉcoloBus cycle”. This is an extremely demanding route consisting of a 5.1 km circuit from the centre of Quebec City to its docks along the St. Lawrence Seaway with road gradients reaching close to 13%, and so was viewed as a means to help establish overall vehicle and system performance, rather than a requirement for this project.

Battery-only and hybrid electric drive modes were examined for these types of cycles. It was found that the CBD route fell within the capabilities of the vehicle design, while the Quebec City “ÉcoloBus cycle” was at the limit of the system capability.

For example, acceleration times were calculated for the bus fully loaded (28 passengers) and moderately loaded (15 passengers). A time of approximately 12 seconds would be required to accelerate to 32 km/h on a 1% grade for any drive mode, closely matching the CBD target of 10 seconds. Therefore, the calculated times to accelerate to typical bus speeds under these conditions were deemed acceptable for a bus application.

Startability was also calculated for a fully loaded bus (28 passengers) and a moderately loaded bus (15 passengers). Even up to severe slopes of 13% found in the Quebec City route, startability was projected to be possible for the moderately loaded bus.

Calculations indicated that a startability performance target of 20% (reflecting starting from a curb or pothole) would not be met. To achieve the 20% startability target, the vehicle would have to be redesigned with gearing that results in a peak force output twice that used, and/or an increase in torque from a redesigned motor.

The gearing and motor design of the prototype vehicle was chosen to meet typical airport shuttle duty in which low speeds and slow accelerations would be the norm. The system was not chosen specifically to meet the high speeds and fast accelerations that may be encountered on freeway driving. A different gearing ratio and possibly a second motor would be required for a vehicle designed to meet such a high-speed duty. For the vehicle to meet both low-speed and high-speed duty, high-low gear shifting would be necessary.

A single, constant efficiency value of 86% was determined to give a reasonable prediction of the overall efficiency of the drivetrain system used in the prototype OCC multi-mode shuttle bus.

The completed vehicle was tested on local roads to examine practical performance issues. Prior to on-road testing, the curb weight of the vehicle was measured to be 6,700 kg (14,765 lb.), which was approximately 300 kg greater than the projected value. This was due to additional hardware added after the initial vehicle integration. Range and acceleration measurements closely matched predicted values. A range of 58 km (36 mi.) was achieved in battery-only drive mode using only 80% of the battery system energy, and a range in excess of 500 km (300 mi.) was projected in hybrid mode. With the vehicle loaded to approximately 92% of its GVWR, the vehicle performed accelerations of 0 to 48 km/h (0 to 30 mph) in less than 18 seconds. Overall, the vehicle successfully demonstrated the multi-mode operation, including driving the vehicle in battery-only mode and various hybrid mode strategies.

# SOMMAIRE

Le projet est né du souhait des exploitants de parcs de véhicules, des sociétés de transport en commun et des organismes gouvernementaux de disposer de véhicules de gamme intermédiaire moins polluants et moins énergivores que les véhicules actuels, mais offrant des performances et une autonomie semblables. C'est que les véhicules au diesel donnent pleinement satisfaction dans la plupart des applications de transport en commun, de transport adapté et de navettes aéroportuaires, mais au prix d'émissions polluantes, que l'on peut relier à la mauvaise qualité de l'air en zones urbaines et, sur une échelle plus vaste, au réchauffement de la planète. D'autres véhicules électriques ou hybrides-électriques ont récemment été mis au point exprès pour des services de navette. Or, ces véhicules, même s'ils donnent satisfaction dans certains contextes bien précis, n'offrent généralement pas l'autonomie ni les performances nécessaires à des applications plus larges.

Overland Custom Coach (OCC) a l'expérience de la construction de petites séries de véhicules à plancher bas destinés aux sociétés de transport en commun et de transport adapté. BET Services Inc. possède pour sa part une vaste expérience de la mise au point de batteries de traction, y compris du développement du matériel et du logiciel de gestion des batteries. Quant à Siemens, elle est un fournisseur de premier ordre de composants électriques et électroniques, et de systèmes de traction électrique. L'équipe de projet, qui réunissait des représentants de ces trois entreprises, considérait comme réaliste ce projet de navette hybride-électrique. Donc, après avoir choisi Siemens pour la fabrication des éléments de la chaîne de traction et pour le développement du logiciel de régulation de haut niveau, et OCC, pour sa technologie de véhicule à plancher bas, BET Services a porté son choix sur les batteries ZEBRA, fabriquées par MES-DEA, les considérant comme les mieux adaptées aux applications envisagées.

Ce projet avait pour objet la mise au point d'un autobus à plancher surbaissé de 28 pieds à propulsion multi-mode (électrique et hybride-électrique) haut rendement, en vue d'une évaluation du véhicule comme navette aéroportuaire et sur des circuits de transport en commun spéciaux. Le véhicule devait pouvoir fonctionner en mode «tout électrique», en mode «tout thermique» et dans une gamme de modes intermédiaires combinant la traction thermique et la traction électrique. Ce concept de traction commutable a été baptisé «multi-mode».

Un prototype de navette à traction hybride-électrique de 28 pi, capable d'un fonctionnement multi-mode, a donc été construit. Des essais ont été réalisés au banc ainsi que dans des conditions simulant le service réel, aux niveaux des sous-systèmes, des systèmes et du véhicule complet. Les essais ont permis de valider le concept multi-mode et ont démontré la possibilité de mettre en service des véhicules à émissions faibles et/ou nulles dans les parcs de véhicules de transport en commun et de navettes aéroportuaires.

Il avait été déterminé que la caisse et le châssis du prototype seraient ceux de l'autobus diesel à plancher surbaissé de 28 pi d'OCC, dont la technologie ELF (pour *Economical Low Floor*) est éprouvée. Fort de son expertise en matière de batteries pour véhicules électriques, BET a choisi de combiner trois batteries ZEBRA haute énergie de 17,8 kWh à la chaîne de traction Siemens pour assurer la propulsion en mode hybride. Ces batteries haute température au sodium/chlorure métallique sont conçues expressément pour les véhicules électriques et hybrides-électriques. Fonctionnant à haute tension et parfaitement hermétiques, elles sont montées en parallèle et dotées de blocs de gestion thermique et électronique incorporés. Un seul moteur de traction Siemens affichant une puissance de pointe de 120 kW a été intégré aux trois batteries ZEBRA et un moteur Ford 5,4 L V-8 fonctionnant à l'essence et au gaz naturel a été relié à un générateur Siemens de 150 kW de puissance de pointe. Des contraintes de poids et de dimensions ont limité à près de 600 V la tension nominale du système de traction. Par

conséquent, le système de batteries ZEBRA choisi pour l'autobus avait une tension nominale avoisinant les 550 V.

Les études de conception avaient conclu à la possibilité d'intégrer la chaîne de traction hybride au véhicule de base. Il a suffi en effet de modifier légèrement l'échappement et les pièces connexes pour placer tous les organes du moteur à combustion interne et du moteur de traction électrique dans le compartiment prévu pour le groupe motopropulseur. L'ensemble moteur/générateur électrique a été monté à la place normalement occupée par le moteur, et le moteur de traction et le réducteur ont été montés là où se trouve habituellement la transmission. Les trois batteries ZEBRA ont été placées sous les sièges, à l'intérieur de l'autobus. Les onduleurs ont aussi été placés dans l'autobus, derrière le siège du conducteur, loin des principales zones d'impact en cas de collision. Trois pompes à chaleur de 5,1 kW (15 000 BTU) destinées au conditionnement de l'air ont été montées sur le toit. Ces pompes sont alimentées en courant alternatif par un onduleur auxiliaire embarqué de 110 V.

Une simple modification des pneus arrière a permis de faire passer le PNBV (poids nominal brut du véhicule) de 7 255 kg (16 000 lb) à 8 617 kg (19 000 lb). Les roues sont restées telles quelles. Toutes les autres caractéristiques techniques principales du véhicule sont demeurées les mêmes après «hybridation».

Le groupe motopropulseur du prototype a été conçu de façon que le moteur de traction reçoive son énergie des batteries (mode tout électrique), de l'ensemble moteur thermique/générateur (mode tout thermique) ou des deux en même temps (mode hybride-électrique). En mode hybride, la source d'énergie et la puissance sont réparties selon diverses configurations. Dans le cas du prototype, un ordinateur embarqué choisissait le mode de fonctionnement et programmait les paramètres en conséquence.

Le moteur à combustion interne n'est pas mécaniquement relié aux roues motrices, pas plus que l'accélérateur au papillon des gaz du moteur. C'est plutôt le système de régulation embarqué qui détermine le régime requis de l'ensemble moteur/générateur, et c'est une puissance électrique qui est délivrée au moteur de traction. Dans le prototype, le temps de réaction du moteur à combustion interne Ford aux régimes demandés était en deçà des attentes. Le mode tout thermique a donc été exclu du projet.

Lorsque le véhicule freine, que le moteur thermique fonctionne ou non, le flux d'énergie est inversé et la batterie récupère ainsi l'énergie de freinage.

Habituellement, l'entraînement des systèmes auxiliaires d'un autobus se fait mécaniquement, directement à partir du moteur ou via un moteur d'auxiliaires distinct alimenté en énergie électrique par la source haute tension principale. Mais dans le cas du prototype, la moitié d'un onduleur double de 70 kVA refroidi à l'air alimentait en courant alternatif les systèmes auxiliaires, y compris les systèmes 12 V. L'autre moitié de l'onduleur double servait à la recharge rapide embarquée. Grâce à un tel agencement, la pompe électrohydraulique de la direction et des freins assistés, les trois pompes à chaleur montées sur le toit et le compresseur d'air de la suspension arrière étaient alimentés en courant alternatif 110 V et fonctionnaient uniquement à l'électricité, avec les avantages que cela comporte : éléments plus petits, plus légers, à meilleur rendement, et offerts en grands volumes. Le système électrique 12 V d'origine du véhicule n'a pas eu à être modifié.

Le véhicule de démonstration du concept multi-mode fourni par OCC comporte deux appareillages de recharge différents, tous deux embarqués :

1) L’appareillage de recharge de nuit (recharge normale) comprend trois chargeurs de 3,2 kW, un pour chaque batterie. Ces chargeurs doivent être branchés au réseau, à une prise de 240 V c.a.
2) Une recharge rapide ou une recharge embarquée grande puissance fait intervenir la moitié de l’onduleur double refroidi à l’air. Comme les batteries ZEBRA ont une tension nominale de près de 550 V c.c., la recharge peut se faire à des tensions avoisinant les 700 V c.c. Comme une recharge grande puissance (haute tension, c.c.) embarquée est possible, on peut se contenter, pour l’appareillage de recharge externe (qui est souvent à l’extérieur), de branchements c.a. basse tension, moins dangereux. Ainsi, l’appareillage externe de recharge rapide de la navette OCC exige un matériel relativement simple et peu coûteux.

Un banc d’essai comportant un dynamomètre d’arbre moteur a été assemblé chez BET Services. Il a servi à mettre à l’essai les chaînes de traction, par modules ou globalement, avant les essais sur route. Ces essais visaient surtout à mettre à l’épreuve les diverses chaînes de traction ainsi que les divers modes de fonctionnement et diverses configurations de mode hybride.

L’itinéraire choisi tant pour les études de conception que pour le programme d’essais au banc comprenait un circuit de centre-ville et de grandes artères. La simulation des déplacements dans un centre-ville comportait des accélérations jusqu’à 32 km/h et à 64 km/h, départ arrêté, sur des chaussées sans dénivellation. Les performances de l’autobus ont aussi été mises à l’épreuve sur le «circuit ÉcoloBus», à Québec. Il s’agit d’un circuit de 5,1 km extrêmement exigeant, qui part du centre de Québec et se rend aux quais aménagés le long du Saint-Laurent, et comprend des pentes de près de 13 p. cent. Cet essai était vu comme un moyen d’établir la performance globale du véhicule et de ses systèmes et débordait les strictes exigences du présent projet.

L’étude des modes tout électrique et hybride-électrique sur ces deux types d’itinéraires a révélé qu’un trajet de centre-ville était à la portée du véhicule, tandis que le «circuit ÉcoloBus» était à la limite des capacités du système.

Par exemple, les temps d’accélération ont été calculés pour l’autobus à pleine charge (28 passagers) et à charge moyenne (15 passagers). Il a été établi qu’il faudrait environ 12 secondes pour passer de 0 à 32 km/h sur une pente de 1 p. cent, quel que soit le mode de fonctionnement, ce qui correspond à peu près à la valeur cible de 10 secondes pour le centre-ville. Donc, les temps calculés pour atteindre les vitesses caractéristiques des autobus dans les conditions étudiées ont été jugés acceptables, ce qui laisse penser qu’un tel véhicule pourrait effectivement servir au transport en commun.

L’aptitude au démarrage a aussi été calculée, encore une fois pour un autobus à pleine charge et à charge moyenne. Même avec les fortes pentes allant jusqu’à 13 p. cent du circuit de Québec, l’aptitude au démarrage de l’autobus a été estimée suffisante, pour autant qu’il soit moyennement chargé.

Les calculs ont toutefois révélé qu’une valeur cible de 20 p. cent de pente de calage (au démarrage à partir du bord du trottoir ou d’un nid de poule) ne pourrait être atteinte. Pour atteindre cette valeur, il faudrait revoir les rapports de démultiplication du véhicule de façon à doubler la force maximale produite et/ou repenser le moteur pour en accroître le couple.

La transmission et le moteur du prototype ont été choisis en fonction des circuits habituellement parcourus par les navettes aéroportuaires, caractérisés par de basses vitesses et des accélérations lentes. Les grandes vitesses et les fortes accélérations nécessaires sur les grandes routes n’étaient pas visées ici. Des rapports de démultiplication différents et, éventuellement, un deuxième moteur seraient nécessaires dans le cas d’un véhicule conçu pour effectuer des trajets grande vitesse. Pour que le véhicule puisse à la fois répondre aux exigences de basse vitesse et de grande vitesse, il faudrait prévoir un mécanisme qui permettrait d’enclencher deux plages de démultiplication différentes.

Une valeur unique et constante de 86 p. cent représente une prévision raisonnable de l’efficacité énergétique globale du système de traction utilisé dans le prototype de navette multi-mode d’OCC.

Pour examiner ses performances en service réel, on a soumis le véhicule à des essais sur route. Avant ces essais, le poids à vide du véhicule était de 6 700 kg (14 765 lb), soit environ 300 kg de plus que la valeur prévue. Ce poids supplémentaire était dû au matériel ajouté après l’intégration initiale du véhicule. L’autonomie et les temps d’accélération mesurés s’approchaient beaucoup des valeurs prévues. Ainsi, une autonomie de 58 km (36 mi) a été réalisée en mode tout électrique, avec une utilisation de 80 p. cent seulement de l’énergie des batteries, ce qui laissait présager une autonomie de plus de 500 km (300 mi) en mode hybride. Chargé à environ 92 p. cent de son PNBV, le véhicule a donné des accélérations de 0 à 48 km/h (0 à 30 mi/h) en moins de 18 secondes. Dans l’ensemble, les essais ont permis de valider l’exploitation multi-mode, y compris du mode tout électrique et de diverses configurations de mode hybride.

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# GLOSSARY OF ACRONYMS

| | |
|---|---|
| AC | Alternating Current |
| ADA | Americans with Disabilities Act |
| BET | Battery Engineering and Testing |
| BMI | Battery Management Interface |
| CBD | Central Business District |
| CMVSS | Canadian Motor Vehicle Safety Standards |
| CSA | Canadian Standards Association |
| DC | Direct Current |
| DICO | Digital Input Control |
| ELF | Economical Low Floor |
| ERMD | Emissions Research and Measurement Division |
| EV | Electric Vehicle |
| FMVSS | Federal Motor Vehicle Safety Standards |
| GVWR | Gross Vehicle Weight Rating |
| HD | Heavy Duty |
| HVAC | Heating, Ventilation, and Air Conditioning |
| IC | Internal Combustion |
| ICE | Internal Combustion Engine |
| IGBT | Insulated Gate Bipolar Transistor |
| MBS | Multiple Battery Server |
| NiCd | Nickel/Cadmium |
| NiMH | Nickel/Metal Hydride |
| OCC | Overland Custom Coach |
| OEM | Original Equipment Manufacturer |
| PID | Proportional/Integral/Derivative |
| SOC | State of Charge |

# 1. THE PROJECT

## 1.1. Introduction

Zero vehicle emission driving is clearly the ultimate aim but at this point in time both batteries and fuel cells have serious limitations as sole sources of propulsion energy. Hybrid systems, however, are at a stage where they offer a near-term solution for reducing emissions rather than eliminating them. The type of hybrid strategy adopted is dependent on the operating environment of the vehicle and its primary function. The technical options for a hybrid system include the size and type of vehicle, the choice of battery, the choice of electric drivetrain, the choice of engine, the power sharing strategy, how to store energy, and how long energy can be stored. The system cost is a major commercial issue and will remain so while volumes are still low.

Choosing a hybrid strategy thus includes choosing appropriate system components, optimizing the operating strategy of the individual systems, and optimizing the operation of the vehicle.

This document presents the description and analysis of a prototype 28 ft. hybrid electric shuttle bus that was built with the capability of battery-only drive, engine-only drive, and a range of hybrid electric drive strategies, termed the “multi-mode” drive concept. Operation of the shuttle bus validated the feasibility of the multi-mode concept and has been used to demonstrate the possibilities of zero and/or reduced emission transit and delivery.

The body of the vehicle was based on the Economical Low Floor (ELF) technology developed by Overland Custom Coach (OCC). The hybrid drive used a high-voltage drive system developed by Siemens, and was powered by ZEBRA (sodium/metal chloride) batteries in conjunction with a Ford 5.4 litre V8 internal combustion (IC) gasoline/natural gas engine. The powertrain was incorporated into the vehicle by BET Services Inc.

The vehicle developed was a low-cost, energy-efficient, low-emission vehicle. Tradeoffs on performance, design, component choice, etc. were made to help ensure that the resulting vehicle was commercially viable.

The project was divided into five phase project tasks, grouped as follows:

Phase 1: Feasibility; Phase 2: Design; Phase 3: Fabrication; Phase 4: Prototype Proving Tests; and Phase 5: In-Service Evaluation

The work that was carried out and the results from each of the phases of the project except Phase 5 are presented in this report. The in-service operation of Phase 5 was not implemented due to perceived liability issues, as well as a lack of resources and overall shortage of time.

## 1.2 Project Definition

This project was part of a commercial development program from which the participating partners hoped to exploit the lessons learned and to create a Canadian-based assembly business for lightweight, user-friendly, reduced-emission commercial vehicles (buses and trucks). The specific goals of this project included:

- Hone the hybrid electric integration skills
- Evaluate the merit of certain component and hybrid electric control options
- Test the first users community with a prototype

The project was a joint collaboration between Overland Custom Coach Inc., a developer of customized vehicles for mass transportation, BET Services Inc., testers and developers of battery systems and associated powertrains, and Siemens, a world-class supplier of electrical drives. The project was supported by the Canadian government.

## 1.3 Participating Companies

### 1.3.1 Overland Custom Coach (OCC)

Overland Custom Coach Inc., established in 1988 and based near London, Ontario, is a developer of customized vehicles for mass transportation. OCC is regarded as an innovator in accessible transportation.

OCC has assembly facilities in Canada and in the U.S. and is well placed to supply to federally funded transit authorities in both countries.

OCC manufactures a range of Federal Motor Vehicle Safety Standards (FMVSS) approved medium duty transit vehicles, typically from 21 ft. to 28 ft. in length. The “Power Clip” vehicle used in this project is the 28 ft. OCC ELF 128 H.D. Transit Bus. It is a semi-monocoque steel body with a Ford E350 based front wheel drive power module.

By participating in this project, OCC gained experience in the development of hybrid electric vehicles, with the ultimate goal of establishing expertise and facilities for the commercialization of such vehicles. OCC will be able to respond to transit and delivery fleet operators that are investigating the possible use of hybrid electric vehicles.

OCC brought to the project its design and manufacturing skills for the development of paratransit custom-built buses. OCC provided the base vehicle with IC engine power plant. In addition, OCC was responsible for adapting and fitting the hybrid electric powertrain into the base vehicle.

### 1.3.2 BET Services Inc

BET Services Inc., incorporated in 1996 in Mississauga, Ontario, works on development programs for automotive traction battery systems. BET was a spin off from an ABB company that had a long history in the development of advanced high-energy batteries and battery control systems for electric vehicles. BET Services was established to focus on the testing and validation of automotive traction battery systems for North American Original Equipment Manufacturers (OEMs).

Using its background in batteries for electric vehicles, BET chose to combine high-energy ZEBRA batteries with the Siemens drivetrain to create the hybrid powertrain. The batteries are high-temperature sodium/metal chloride chemistry designed specifically for use in electric and hybrid vehicles. They are parallel-connected, self-contained, high-voltage units, complete with thermal and electronic management systems.

Involvement in this project has helped BET to expand its experience in electric powertrain hardware and software. BET's future objective is to provide technical and commercial support for hybrid powertrain systems for buses developed and sold by OCC or other suppliers of transit or medium-duty vehicles.

BET provided the technical knowledge for the modeling and systems integration of the hybrid powertrain into the bus. BET provided the test equipment and facilities to integrate the hybrid drive components into the vehicle. BET purchased the drivetrain components from Siemens and the batteries from MES-DEA. The on-board charging/auxiliaries inverter was not purchased from Siemens. BET also purchased additional drive components from Siemens for the test rig. In addition, BET was the coordinator for project administration.

### 1.3.3 Siemens

Siemens is a world-class supplier of electrical and electronic components and major electric traction systems. It has experience with diesel electric locomotives, diesel electric boats and diesel electric buses. Siemens has also built hybrid bus systems using fuel cells, NiCd batteries and supercapacitors.

Siemens built the electric drive components used in this project and sold them to BET at a subsidized price. The components included a 70 kW AC traction motor, an 85 kW AC generator, and the IGBT inverters that control the traction motor and match the generator output to the battery.

By teaming with OCC and BET, Siemens is demonstrating the latest European traction technology to the North American market. The objective is to present itself as the major supplier of traction equipment components to the North American market, particularly for medium-duty vehicles built by OCC and other operators.

Engineering skills were the key input to this project by Siemens. Siemens has developed the special software for controlling power sharing between the IC engine and batteries during hybrid electric drive. It has also developed the electronic interfaces between the drive system and the batteries, and the drive system and the vehicle control system.

### 1.3.4 Transport Canada – TDC

The Transportation Development Centre (TDC) is a Transport Canada organization dedicated to the development and application of new technology in the transportation sector to improve safety and productivity, and to reduce the impact of transportation on the environment.

TDC, via its own R&D budget and the available interdepartmental Program of Energy R&D (PERD) managed by Natural Resources Canada (NRCan), has led an Electric Vehicle and Hybrid Electric Vehicle technology development program, together with an advanced bus technology program, aimed at reducing the energy consumption and emissions from bus transportation through the development and application of advanced electric propulsion systems and weight reduction initiatives.

TDC hopes to stimulate the development of Canadian expertise and product in electric propulsion applied to heavy-duty vehicles used in urban areas and to promote the deployment of such vehicles in Canadian cities.

## 1.4 Objectives and Scope

The objective of the project was to develop a multi-mode energy-efficient, low floor, 28 ft. battery and hybrid electric bus for evaluation in an airport shuttle application and some specialized transit applications.

The scope of this multi-phase project involved the development of an electric drivetrain, powered by a battery pack or a combination of a battery pack and an IC engine-powered electric generator, and its integration into an already commercially available OCC ELF 28 ft. low floor bus.

The work covered bus performance computer simulation, component selection, and design and testing of control systems for the batteries and the high-power charger, the motor, the generator, the auxiliary systems' electric drive, and the vehicle. The control system was optimized for both battery-only mode and hybrid mode configurations on a test bench dynamometer system, which was also developed during the course of the project.

The work also involved the integration of all these systems into an existing bus to produce a prototype multi-mode electric bus that underwent proving tests on the road. Ultimately, the multi-mode bus will be evaluated in specialized transit applications in Quebec City (ÉcoloBus evaluation project) and other Canadian cities.

In a separate initiative, the promoters plan to build and sell pure battery electric and other IC engine-hybrid electric buses to interested transit and commercial entities.

### 1.4.1 Project Tasks

The project was divided into five phase project tasks, grouped as follows:

Phase 1: Feasibility
- Define bus duty cycle and load characteristics.
- Use recognized engineering analysis and simulation approaches to define the electric propulsion system and the thermal management system generic designs to help guide selection of key components.
- Evaluate the battery charger systems, the electric drive and control systems for the auxiliaries, and the physical location of these components in a 28 ft. OCC ELF bus.

Phase 2: Design
- Design the electrical, mechanical and data interfaces between the OCC bus and the Siemens electric drive and related control systems.
- Engineer and source the IC engine electric power generator.
- Program the vehicle CAN (Control Area Network) interface to the battery pack control system.
- Engineer bus body and chassis modifications to package the electric drive components, the Heating, Ventilation, and Air Conditioning (HVAC) system, and the auxiliary systems.
- Design and source a speed reduction unit for the traction motor.
- Design and build a laboratory test bench to evaluate and optimize the performance of the various battery configurations for the optimized battery-only mode and “ICE-battery” hybrid electric drive configurations.
- Design and build the on-board and off-board components to allow high-power daytime interim battery charging.

Phase 3: Fabrication
- Assemble the powertrain and battery charging components around the laboratory test bench and conduct performance optimization runs.
- Integrate the IC engine, generator, electric drive components and battery packs into the multi-mode electric drive bus.

Phase 4: Prototype Proving Tests
- Run tests of the completely assembled bus on the lab test bench to validate vehicle range and performance and battery state of charge (SOC) estimates under various system control modes and duty cycles.
- Verify performance of on- and off-board battery charging components.
- Perform on-road validation tests to confirm bus performance targets.

Phase 5: In-Service Evaluation
- Perform independent evaluation of vehicle performance based on operational service.

## 1.5 The OCC Multi-Mode Electric Bus

### 1.5.1 Summary

The development of this vehicle was in recognition of the desire by progressive cities and corporations to evaluate the benefits of electric and hybrid electric vehicles in their transit and delivery fleets. Although this was an R&D project, the design must also have demonstrated that it was capable of meeting real-world applications and challenges.

Overland Custom Coach has a well-proven, diesel-powered, low floor, 28 ft. shuttle, the ELF. It is used primarily for paratransit and airport shuttle duties. With a hybrid powertrain, the same vehicle platform fitted with different bodies would also be suitable for airport ground support and the urban delivery truck market.

Such applications have appeal as entry markets for hybrid vehicles due to their predictable routes.

The above requirements dictated to a large extent the hybrid strategy. The drivetrain components could not be too heavy, otherwise payload capacity would be lost. This dictated the use of a high-voltage (e.g., 600 V) water-cooled system for the generator, the control inverters and the traction motor. The batteries also needed to be high voltage to be compatible with the electrical drivetrain.

Large vehicles require significant quantities of energy exchange for any mode of hybrid operation. The batteries thus need to have a high energy density, otherwise their weight penalty becomes unacceptable. Batteries with high energy density lead to “charge depleting” operating strategies that allow significant battery-only, zero emission driving. Such a system could also be operated in “charge maintaining mode” in which the batteries undergo only shallow cycles, but this results in the vehicle carrying “unused kWh” stored in the batteries (and hence excess weight).

The operating strategy should seek to reduce disproportionate emissions and aim to reduce the overall fuel consumption that dictates the general level of emissions. In stop-start applications found with an urban bus or delivery van, the operating strategy could be to eliminate idling and perform all accelerations from rest electrically. The engine could be spun-up by the generator and the injectors enabled at 1600 rpm, for example, to avoid high emission conditions.

The general level of fuel consumption for stop-start vehicles can be reduced by recapturing the energy normally lost to heat during braking, termed “regenerative braking”. This is achieved by allowing the traction motor to run as a generator during braking, and capturing the energy in the battery. This energy can be used later for traction purposes or to reduce engine power peaks, both of which save fuel. This also raises the issue of how power is shared between the engine and the battery.

### 1.5.2 Vehicle Design

The bus body and chassis for the prototype vehicle were pre-selected based on an existing vehicle structure already developed by OCC: the 28 ft. ELF diesel shuttle. This is a low floor vehicle used primarily for paratransit and airport shuttle duties.

The issues for the vehicle design of the prototype OCC multi-mode shuttle bus were thus:

- feasibility of packaging a hybrid drivetrain while maintaining the 28 passenger capability within a new GVWR (gross vehicle weight rating);
- maintaining ergonomics, ease of service and repair, fueling ease and safety, crashworthiness, and visibility at the same level as the base vehicle; and
- validating the claim that the hybrid strategy produces a net reduction in emissions with the heavier vehicle.

A photo of the prototype vehicle produced for this project is shown in Figure 1, and the final layout design is shown in Figure 2.

The design studies had indicated that the hybrid powertrain could be packaged in the standard vehicle, and this was ultimately achieved. With some slight modifications to the exhaust piping and related components, all of the IC engine and electric drive components fit within the powertrain area of the base vehicle. This approach allowed the body area to retain total flexibility. This is the same "power clip" design approach used by OCC for its standard IC engine vehicles.

The engine generator was mounted in the normal engine position and the traction motor and reducer were mounted in the area normally occupied by the transmission, as shown in Figure 3. Figure 4 shows the location of one of the three ZEBRA batteries, which were mounted under the seats inside the bus. Figure 5 shows the location of the inverters, which were also mounted inside the bus behind the driver's compartment. The high-voltage power components were all well protected, away from the major crash zones. The three heat pumps for vehicle climate control were mounted on the roof.

As with any hybrid electric vehicle, the batteries and hybrid drive components take up a large percentage of weight capacity that might otherwise be available for payload. By modest upgrading of just the rear tires, the GVWR of the vehicle was raised from the base of 7,255 kg (16,000 lb.) to 8,617 kg (19,000 lb.). To accomplish this, the single rear tires were changed to 265/70R x 19.5 radials from 245/70R x 19.5 radials. No changes were made to the wheels to accommodate these tires. All other design specifications of the hybridized vehicle remained the same as the base vehicle.

**Figure 1** Prototype 28 ft. ELF multi-mode hybrid electric shuttle bus

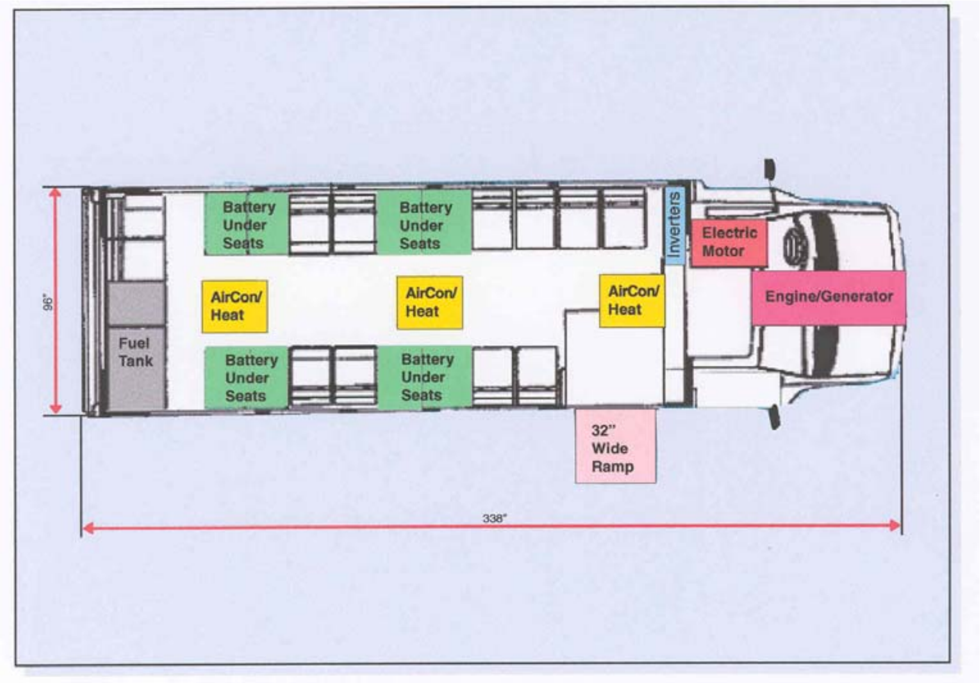
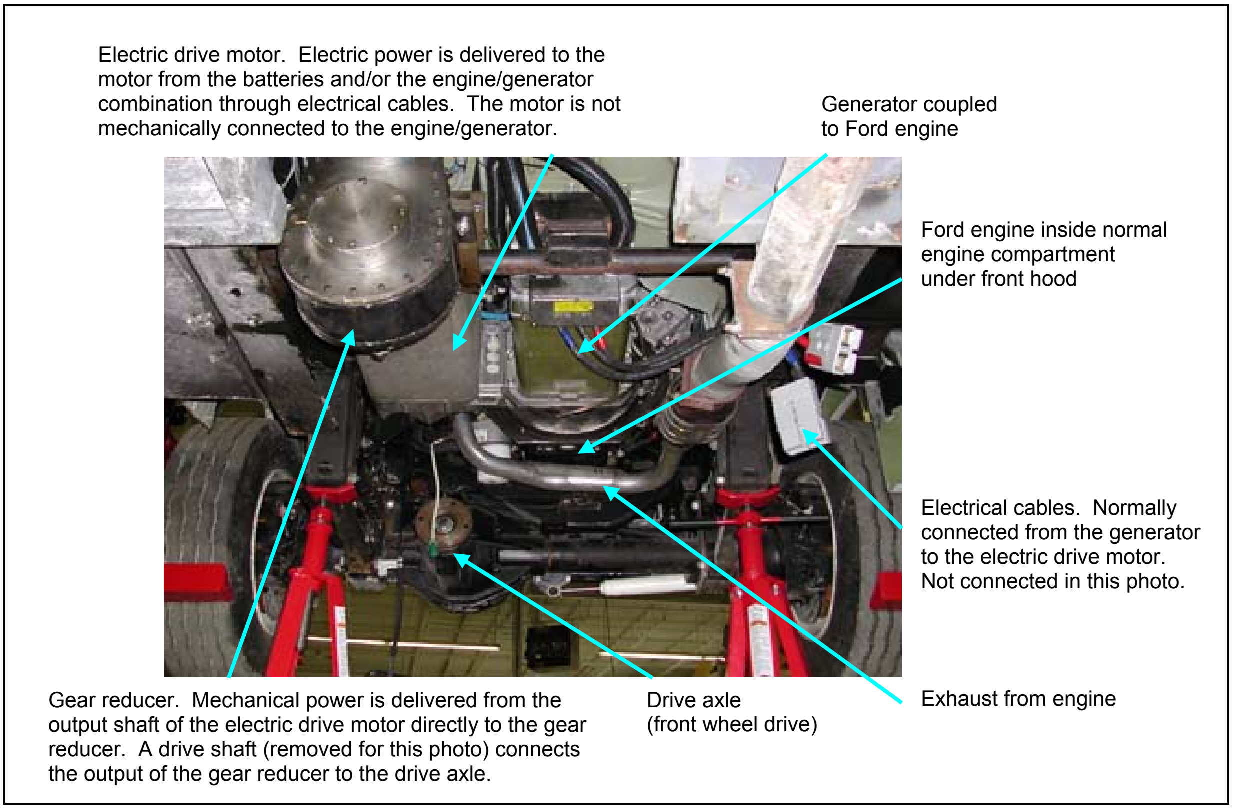


**Figure 2** Plan view, internal dimensions, battery layout, and seating arrangement of the prototype bus



Electric drive motor. Electric power is delivered to the motor from the batteries and/or the engine/generator combination through electrical cables. The motor is not mechanically connected to the engine/generator.

Generator coupled to Ford engine

Ford engine inside normal engine compartment under front hood

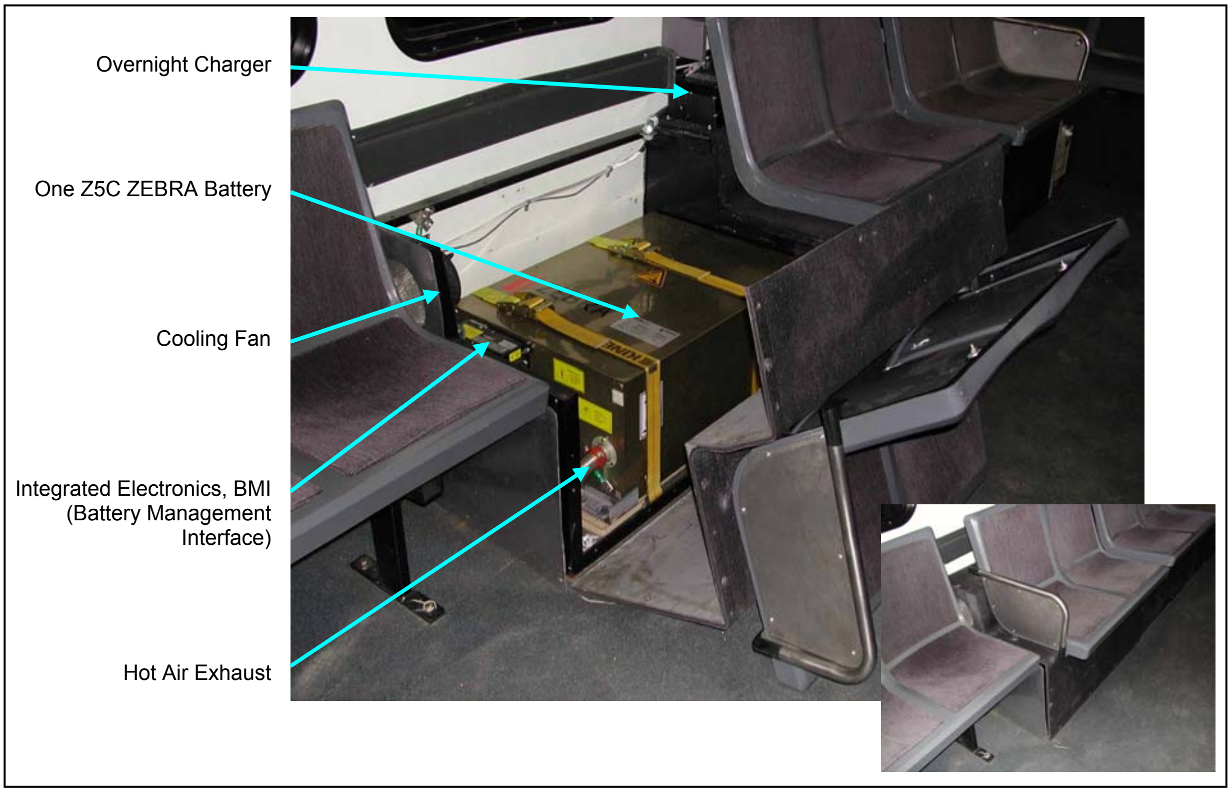
Electrical cables. Normally connected from the generator to the electric drive motor. Not connected in this photo.

Gear reducer. Mechanical power is delivered from the output shaft of the electric drive motor directly to the gear reducer. A drive shaft (removed for this photo) connects the output of the gear reducer to the drive axle.

Drive axle (front wheel drive)

Exhaust from engine

**Figure 3** View of drivetrain components underneath the bus (looking forward to the front wheels)



Overnight Charger

One Z5C ZEBRA Battery

Cooling Fan

Integrated Electronics, BMI (Battery Management Interface)

Hot Air Exhaust

**Figure 4** Installation of one ZEBRA battery under perimeter seating

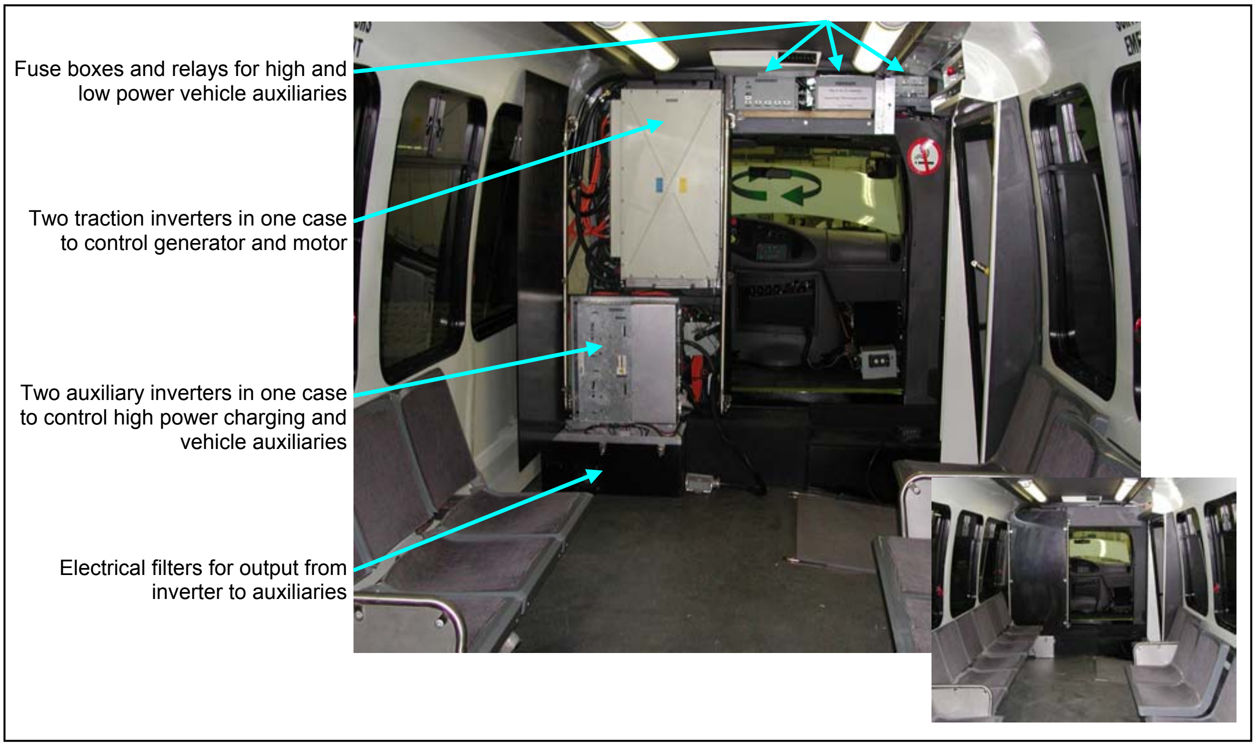


**Figure 5** **View of power electronics and components inside the bus (looking forward to the driver's compartment)**

### 1.5.3 Powertrain

The architecture of the powertrain used in the OCC multi-mode shuttle is shown in Figure 6.

The engine mechanically drives the generator that produces 3-phase AC electrical power. The inverter changes the 3-phase AC electric output to DC and regulates its voltage to match that of the load voltage of the battery. This varying voltage is converted back to AC in a second inverter, which is then used to control the AC traction motor. The traction motor can thus receive its energy from the battery (battery-only mode), from the engine via the generator (engine/generator-only mode), or from a combination of the two (hybrid electric mode). In hybrid mode the source of energy is shared, as is the power (i.e., the rate of energy usage).

The output from the generator inverter dynamically follows the ever-changing battery voltage (a function of load) and allows the power (and/or energy) to be shared between engine and battery according to the operating strategy (i.e., the software). If the engine is switched off (e.g., when the vehicle is at rest or when it is operating in battery-only mode) all energy flow is from the battery to the traction inverter. Though not shown as an energy flow arrow in Figure 6, the engine can be started or re-started via the generator using energy from the 550 V batteries (rather than starting by the normal OEM 12 V ignition system).

When the vehicle brakes with or without the engine running, then the energy flow is reversed allowing the battery to capture the regenerative braking energy. The AC traction motor acts as a generator and since the inverter is inherently a two-way device, it passes DC energy back to the battery at the correct voltage for the battery to accept the charge. Figure 6 shows all energy flow into the battery, including regenerative braking, direct feed from the generator, and energy from the on-board charger when used.

Capture of regenerative braking energy on a bus is very important since greater than 15% of total energy usage is potentially available for recapture.

For size and weight reasons the nominal voltage of the drive system should be near 600 V, and water-cooling of the rotating machines and inverters is essential. If the system were to be air-cooled and have a nominal voltage of about 300 V, the comparable cost, size and weight of the electric drivetrain would increase approximately twofold. Therefore, the ZEBRA battery system chosen for the bus had a nominal voltage in the region of 550 V.

The ZEBRA battery is a high-temperature battery and so 2 to 5 kW of convenient, high-grade waste heat can be provided by the batteries that can be used to augment vehicle heating, etc.

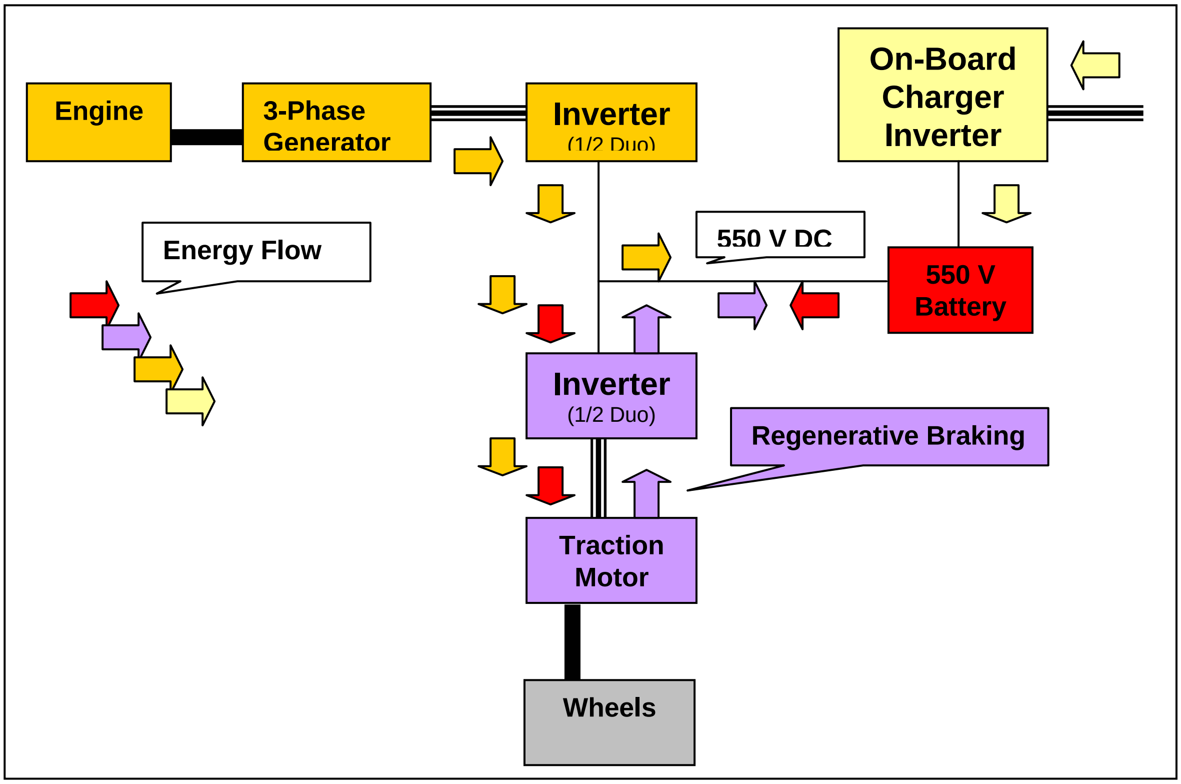


**Figure 6 Powertrain architecture of the prototype shuttle bus**

### 1.5.4 Auxiliaries

Buses using diesel electric drives, engine hybrid drives, and fuel cell prototypes have traditionally opted for the auxiliaries to be mechanically driven either directly from the engine or from a large auxiliaries motor electrically powered from the main high-voltage supply (i.e., the generator or the fuel cell). Powering the auxiliaries this way on a hybrid is bound to increase weight and occupy more space since there is an additional large AC motor that has to be fed from a high-power inverter.

For hybrids with the IC engine running continuously, the auxiliaries can be driven mechanically from the generator shaft, thus avoiding the extra motor/inverter.

With either of these options, normal engine driven auxiliaries can be used and it keeps the configuration close to a conventional diesel engine. This is a pragmatic approach with obvious advantages for a large 40 ft. bus.

In 40 ft. buses, space, weight and energy efficiency have traditionally not been seen as a priority. The rotating electrical machines feeding the auxiliaries all have to work at variable engine speed and give adequate output at very low engine speeds for safety reasons. As hybrid vehicles, auxiliaries also have to be present for safety reasons when the vehicle is operational but the engine is not running, if that is part of the hybrid strategy.

For the smaller shuttle, packaging a large auxiliaries motor configuration is a problem. The auxiliaries motor typically will have the same frame size as the generator and traction motor, but it will be shorter. To this length has to be added the pulleys and the belts for the conventional rotating auxiliaries drives. This results in a large unit that must be packaged in a smaller vehicle along with the traction motor, the generator and the batteries. Furthermore, the added weight of the motor and related components is a step in the wrong direction.

Physical size and weight of the auxiliaries are important issues, but energy efficiency is also particularly important during battery-only driving. Electrically driven pumps and motors are typically more efficient, smaller, and lighter, and are available in high volumes through the recreational vehicle (RV) industry. Therefore, the prototype bus incorporated the auxiliaries system shown in Figure 7 in which one half of a “duo” inverter was used to provide 110 V AC power to the auxiliary units including any 12 V systems, and the other half was used for on-board high-power charging.

A 70 kVA, air-cooled, duo inverter was chosen for control of the auxiliaries + on-board high-power charging applications. For standardization reasons the obvious solution would have been to use a water-cooled Siemens duo inverter to match that used for the traction system, but this was not possible due to software issues.

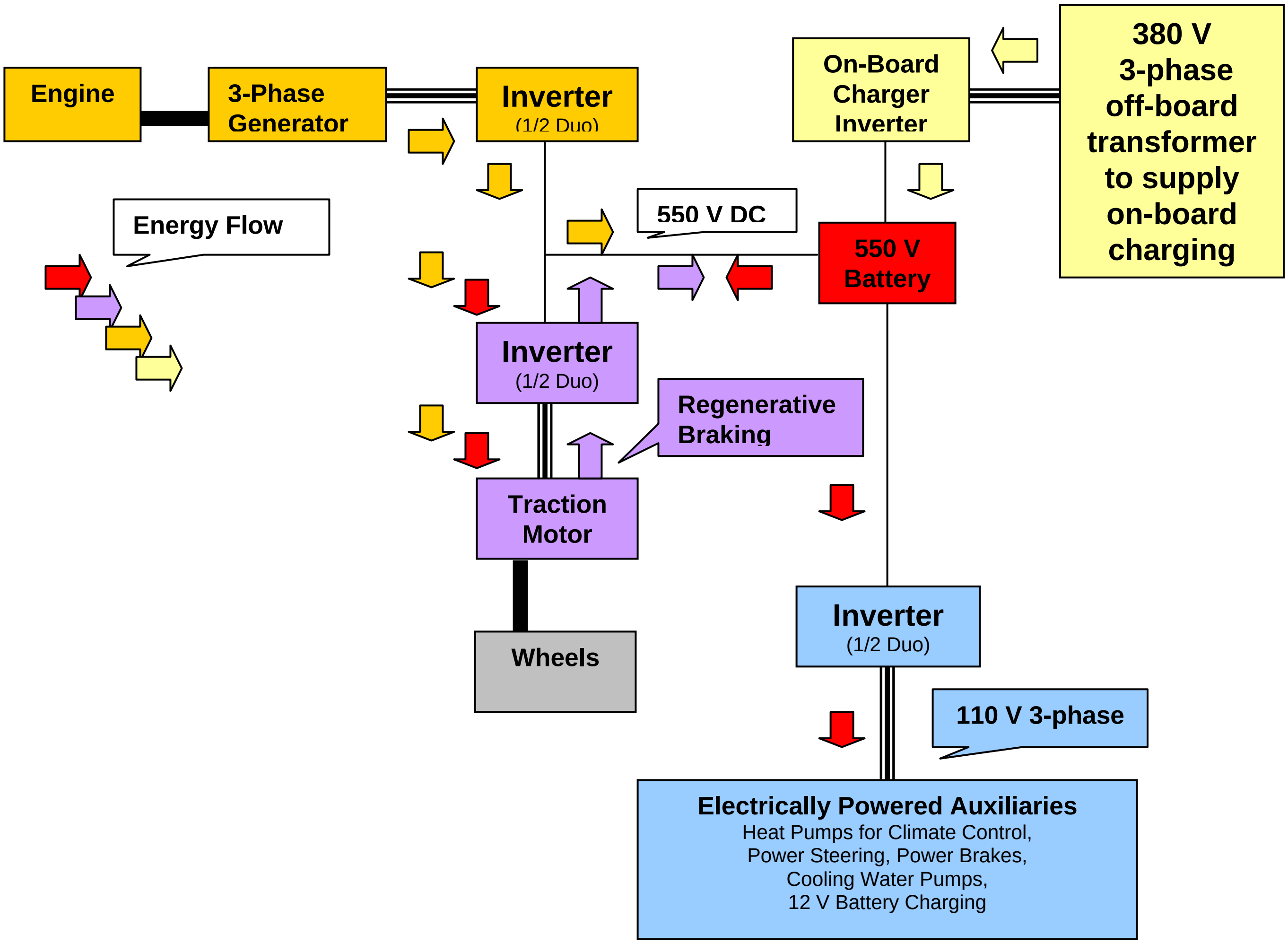


**Figure 7** System showing auxiliaries power feed and off-board infrastructure for on-board charging

### 1.5.5 Performance Targets

*Base Vehicle*

This project was based on the conversion of an existing, IC engine vehicle to a hybrid electric drive.

The IC-powered base vehicle used was the OCC ELF 128 H.D. transit vehicle. This is a 28 ft. low floor medium-duty bus and is certified to meet all FMVSS/CMVSS requirements and applicable ADA and CSA regulations.

The cab portion of the vehicle is based on Ford E350 components. The normal engine used by OCC for the base ELF 128 H.D. transit vehicle is the Ford 7.3 litre diesel engine. For the prototype hybrid electric bus, however, a Ford 5.4 litre V8 gasoline/natural gas engine was used.

The body construction is a highly durable monocoque body of rust-resistant steel alloys and fiberglass outer shell with a high gloss coat finished exterior surface. The overall external dimensions are 337 in. L x 96 in. W x 100 in. H with an interior cargo area of 242 in. L x 92 in. W x 81 in. H. Passenger windows are approximately 45 in. x 36 in. glazed 31% gray light-density, tempered safety glass.

The brake system comprises hydraulic 15 in. front disc brakes with dual-piston calipers, and self-adjusting 15 in. x 5 in. drum brakes in the rear. The front axle is rated at 8,000 lb. with a standard final drive ratio of 5.13:1. Front suspension uses heavy-duty coil springs with stabilizer bar and shock absorbers. The rear axle is rated at 12,000 lb. Rear suspension is self-leveling with air springs and shock absorbers. Front tires are normally 245/70R x 19.5 radials. The single rear tires are normally 245/70R x 19.5 radials. For the prototype hybrid electric bus, however, the single rear tires were changed to 265/70R x 19.5 radials to allow the GVWR to be increased.

In its base diesel form, the vehicle has a GVWR of 7,255 kg (16,000 lb.) and a maximum passenger capacity of 28 passengers with a perimeter-seating layout. For the prototype hybrid electric bus, however, the GVWR was increased to 8,630 kg (19,000 lb.). The passenger capacity and seating layout remained the same.

The ELF provides easy access for the physically challenged by means of a low floor height of only 15 in. from the ground with the vehicle empty. A simple foldout ramp eliminates costly service problems, down time, and safety factors associated with mechanical lifts. A 12 V power ramp is available as an option. The ELF also includes a curbside kneeling feature to make wheelchair access even easier.

*Vehicle Performance*

The OCC ELF multi-mode hybrid electric vehicle had performance targets shown in Table 1.

**Table 1**
**Performance Targets for Multi-Mode Prototype Vehicle Compared to Conventional ELF**

| Item* | Conventional (Base) ELF 28 ft. Diesel | Targets for Multi-Mode 28 ft. Hybrid Electric Prototype (3 batteries) | Targets for Prototype 28 ft. Vehicle as Pure Electric (5 Batteries) |
|---|---|---|---|
| Payload - Seated Passengers | 23 | 23 | 23 |
| - Wheelchair locations | 2 | 2 | 2 |
| - Capacity | 2,455 kg / 5400 lb. | ≥ 1,815 kg / 4000 lb. | ≥ 1,815 kg / 4000 lb. |
| Top Cruise Speed | 110 km/h / 68 mph | ≥ 70 km/h / 43 mph | ≥ 70 km/h / 43 mph |
| Maximum Speed | 120 km/h / 74 mph | ≥ 80 km/h / 50 mph | ≥ 80 km/h / 50 mph |
| Acceleration to 32 km/h | ≤ 11.5 sec | ≤ 10 sec | ≤ 10 sec |
| Range | 640 km | ≥ 60 km battery-only,<br>≥ 250 km hybrid | ≥ 100 km battery-only |
| Startability at 0 km/h | ≥ 20% grade | ≥ 20% grade | ≥ 20% grade |
| Gradeability at 35 km/h | ≥ 9% grade | ≥ 13% grade | ≥ 13% grade |
| Meets all FMVSS, incl. braking | YES | YES | YES |

*Values given for maximum passenger loading and 0% grade unless otherwise specified.
For the Conventional ELF, the total payload capacity equates to a maximum of 36 passengers.
For the Multi-Mode bus (3 batteries), total payload capacity equates to a maximum of 28 passengers.
For the Pure Electric bus (5 batteries), total payload capacity equates to a maximum of 28 passengers.
For the purposes of this table, the weight difference to replace the engine/generator with 2 more batteries and additional electronics is taken to be zero, so the overall payload capacity between the Multi-Mode and Pure Electric vehicles stays the same.

In addition to the performance values targeted in Table 1, the converted hybrid electric vehicle was intended to be equivalent to or better than the base vehicle for all other generic or functional specifications, including:

- Ergonomics
- Ease of repair
- Fueling ease and safety
- Crashworthiness
- Driver and passenger visibility
- Overall vehicle dimensions, including passenger space
- Low floor construction
- Ramp for wheelchair access

# 2. TECHNICAL FEASIBILITY

## 2.1 Duty Cycles

The focus of the design studies and bench test program was the Central Business District (CBD) + Arterial cycle, shown in Figure 8 and Figure 9. Battery-only and hybrid electric drive modes were developed based on this type of cycle.

The CBD simulation that was used (0% grade) requires accelerations from 0 to 32 km/h in 10 seconds as well as accelerations from 0 to 64 km/h in 29 seconds. The route also requires the vehicle to travel at constant speeds of 32 km/h (for periods of 18.5 seconds) and 64 km/h (for periods of 22.5 seconds). The average power required over a single CBD cycle using the prototype vehicle with typical loading is about 17 kW, so the route is not overly demanding.

Performance was also examined for the Quebec City “ÉcoloBus route”. This is an extremely demanding route from the centre of Quebec City to its docks along the St. Lawrence Seaway, and so was viewed as a means to help establish overall vehicle and system performance, rather than a requirement for this first project.

Details for the Quebec City ÉcoloBus route were provided by Mr. Claude Achim from STCUQ (Société de transport de la Communauté urbaine de Québec). The route consists of a 5.1 km circuit starting at Quebec City’s seaside port, rising to the centre of the city’s tourist area roughly 60 m above sea level, then returning back to the port at sea level. From the information provided, one cycle of the route requires approximately 22 minutes to complete, with typical drive speeds of 20 to 30 km/h. The steepest slopes recorded are 12.9%. The average power required over a single ÉcoloBus route using the prototype vehicle with typical loading is about 23 kW, so the route can be viewed as being more demanding than the CBD cycle.

The physical characteristics of the Quebec City ÉcoloBus route, as well as the general power requirements calculated for the 28 ft. shuttle to perform one cycle of the route, are graphically displayed in Figure 10 and Figure 11.

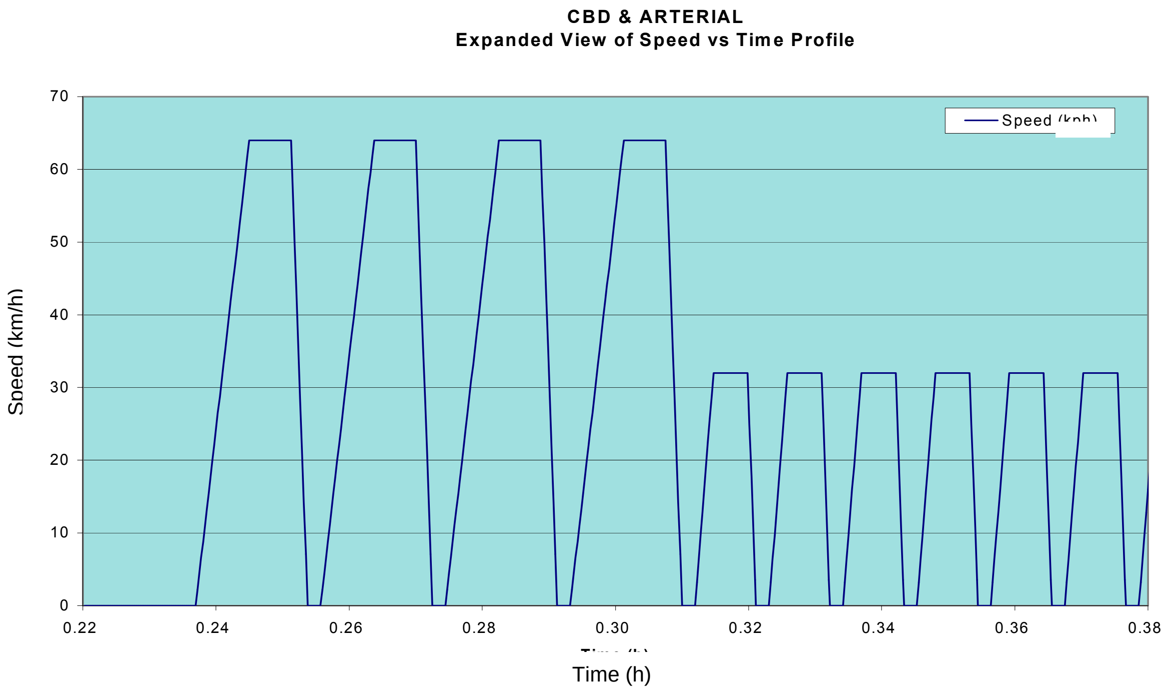


**Figure 8 Profile of CBD + Arterial Cycle**

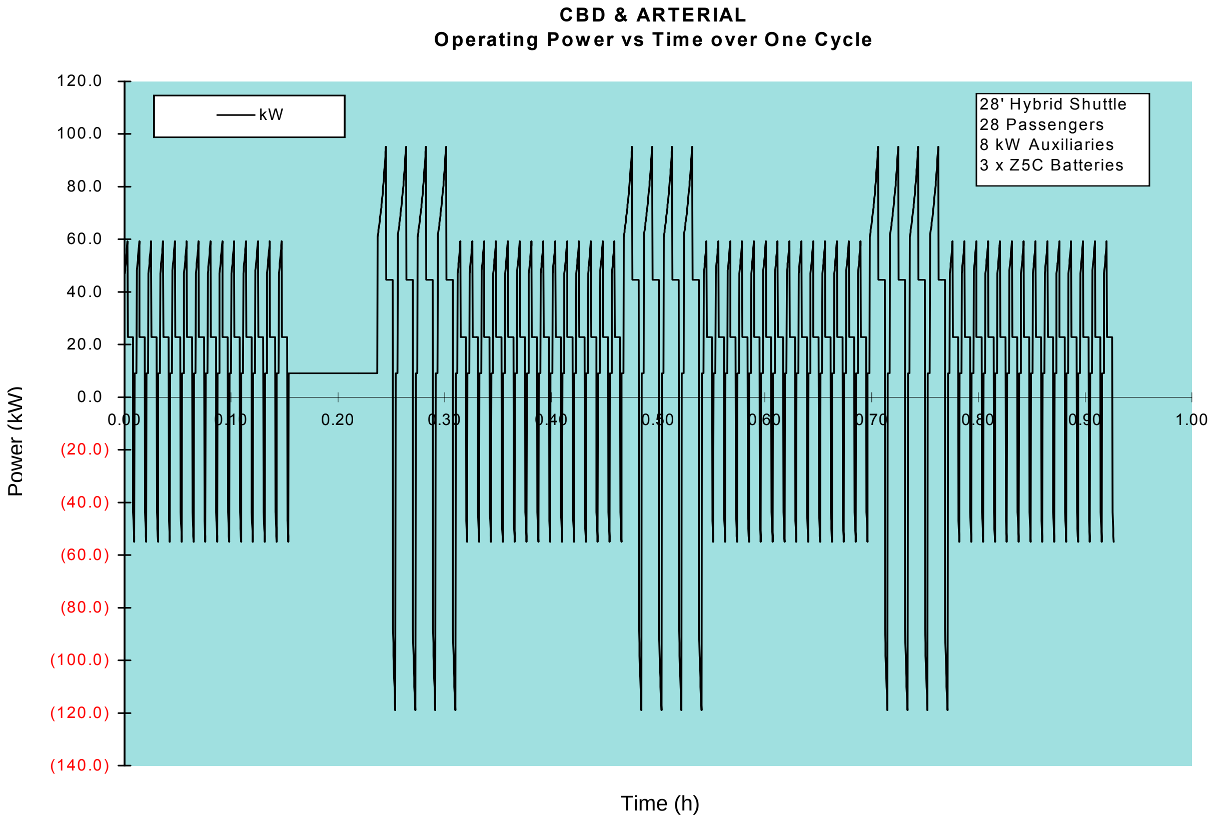


**Figure 9 Calculated power requirements for the Multi-Mode Bus to perform the CBD + Arterial Cycle**

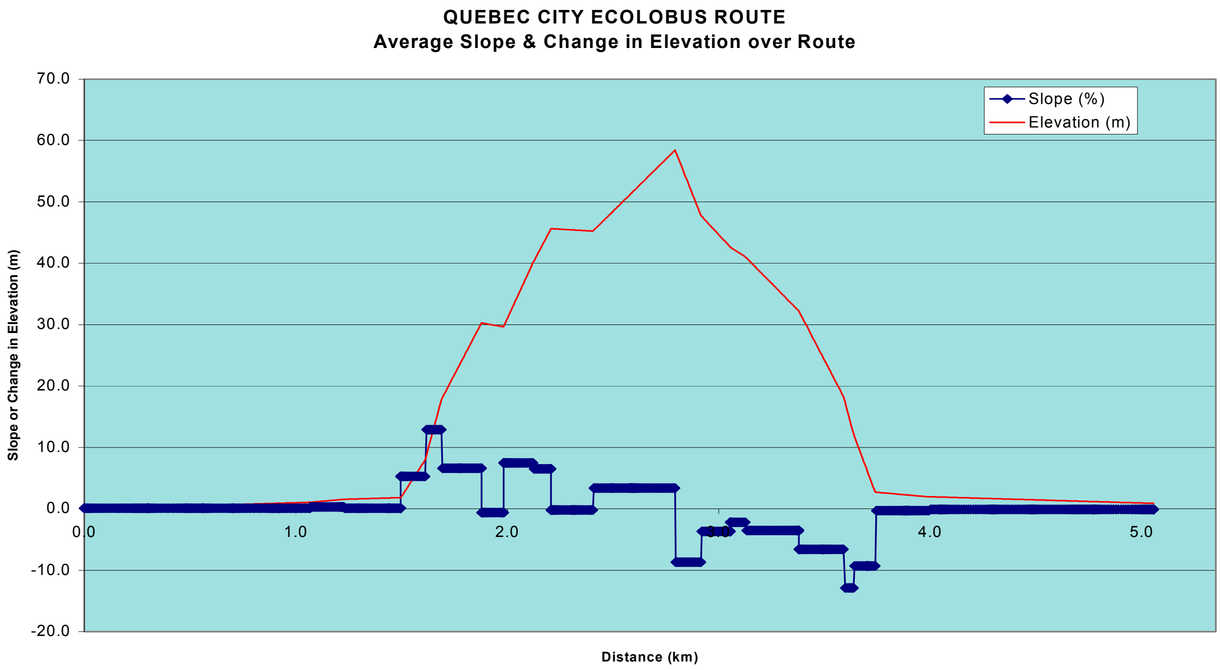


**Figure 10** Quebec City ÉcoloBus Route

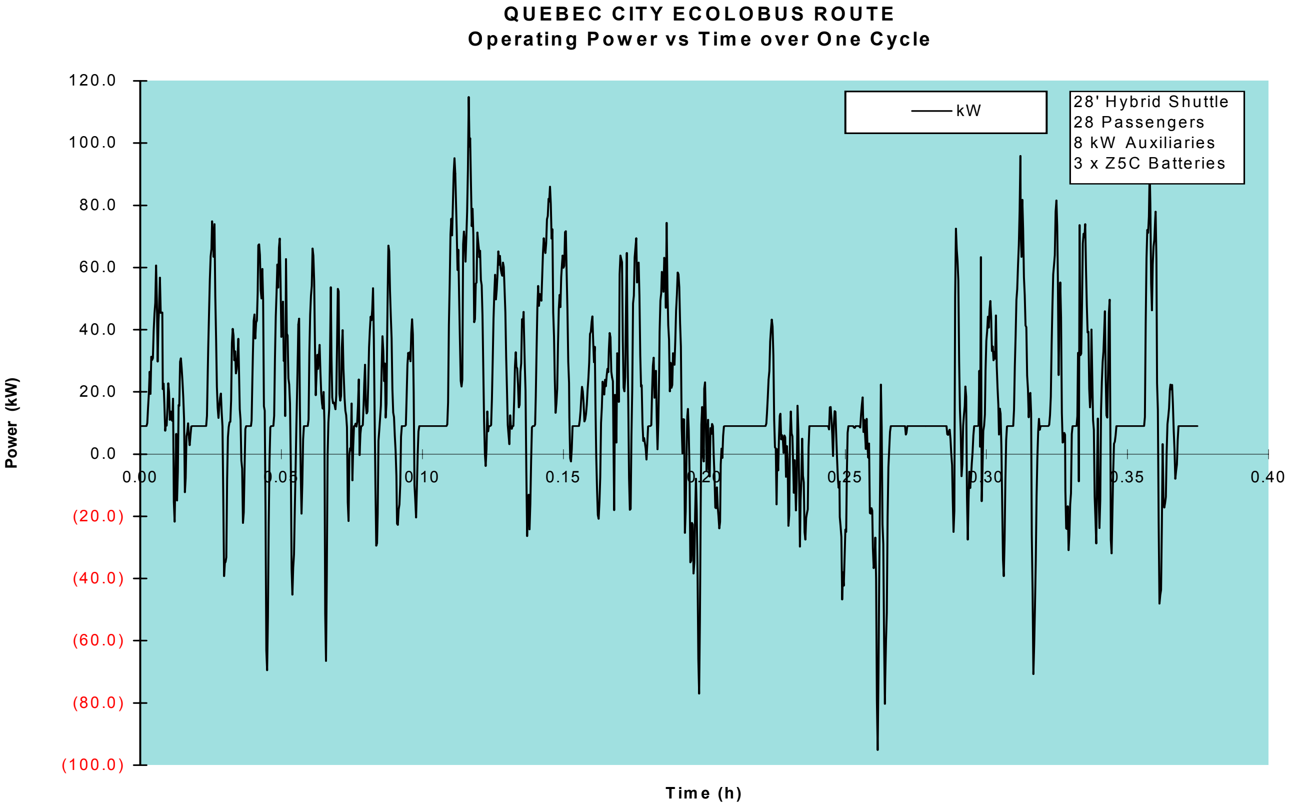


**Figure 11** Calculated power requirements for the Multi-Mode Bus to perform the Quebec City ÉcoloBus Route

## 2.2 Performance Issues

Standard mathematical equations were applied in order to examine the performance required for the bus. The basic form of the equation to calculate the power required to overcome the external forces at the wheels during constant speed driving is as follows (refer to Table 9 for relevant parameters):

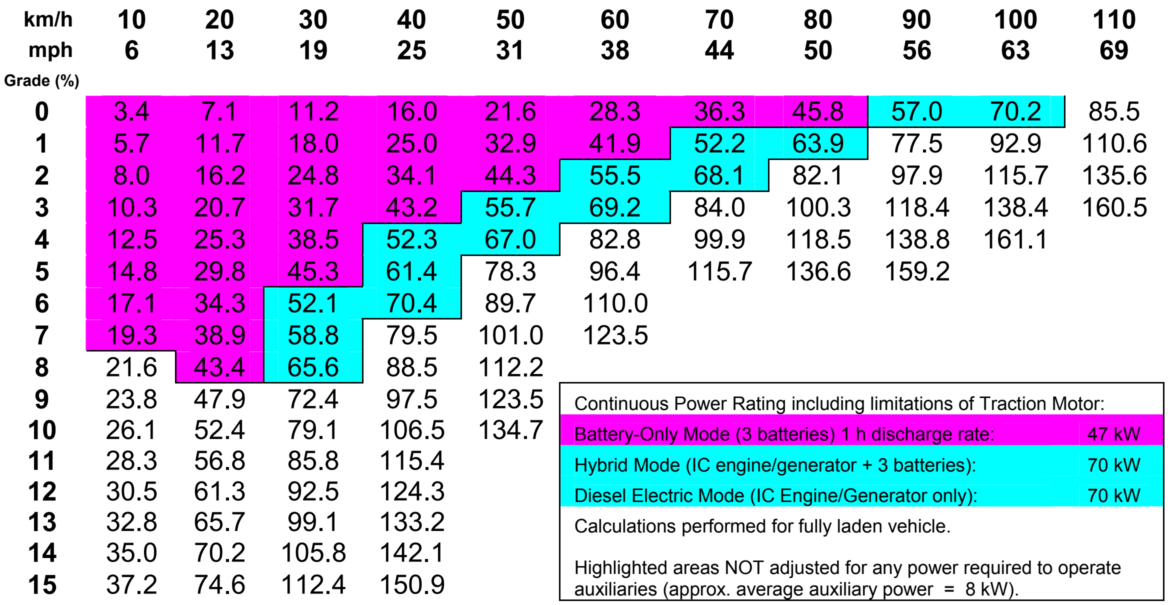
Power required at the Wheels = (Power required to overcome Rolling Resistance) + (Power required to overcome Hill Climbing) + (Power required to overcome Air Drag)

The power required at the wheels for the bus as designed to travel at a constant speed on a constant slope with 28 passengers (fully loaded) is indicated by each of the values shown in Table 2. The purple-highlighted values in the upper left portion of the table indicate the approximate conditions for continuous operation that the vehicle can meet under battery-only mode, in which estimated motor and transmission efficiencies were taken into account. The blue-highlighted values indicate the approximate limits that the vehicle can meet under hybrid mode or engine/generator-only mode. Values not highlighted indicate conditions for continuous operation that the vehicle cannot meet. The values in the lower left portion of the table are not highlighted due to the limitations of continuous operation of the traction motor, which limits the overall powertrain continuous performance at low speeds.

The boundaries of vehicle operation shown in Table 2 are approximate, and indicate conditions for continuous operation. The boundaries will increase for short duration, maximum power operation, and for operation with fewer passengers. The boundaries will be directly reduced by the amount of auxiliary or other parasitic power requirements.

Under battery-only mode (with three batteries), speeds of up to approximately 20 km/h can be sustained under almost any typical road gradients, while speeds of about 70 km/h can be sustained only at very low road gradients. Of course, more aggressive conditions can be met for short durations where the motor can be pulsed to higher power outputs. In general, this meets the vehicle performance requirements for a bus application as indicated in Table 4. The gradeability target for sustained speeds in Table 4 of 13% at 35 km/h requires a power of roughly 120 kW. This target is achievable in hybrid mode for short durations but cannot be met in battery-only mode with three batteries.

## Table 2
## Gradeability Calculations for the Multi-Mode Prototype Vehicle



**Vehicle Power Required to Maintain Constant Speed (kW)**

| **km/h** | **10** | **20** | **30** | **40** | **50** | **60** | **70** | **80** | **90** | **100** | **110** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **mph** | **6** | **13** | **19** | **25** | **31** | **38** | **44** | **50** | **56** | **63** | **69** |
| **Grade (%)** | | | | | | | | | | | |
| **0** | 3.4 | 7.1 | 11.2 | 16.0 | 21.6 | 28.3 | 36.3 | 45.8 | 57.0 | 70.2 | 85.5 |
| **1** | 5.7 | 11.7 | 18.0 | 25.0 | 32.9 | 41.9 | 52.2 | 63.9 | 77.5 | 92.9 | 110.6 |
| **2** | 8.0 | 16.2 | 24.8 | 34.1 | 44.3 | 55.5 | 68.1 | 82.1 | 97.9 | 115.7 | 135.6 |
| **3** | 10.3 | 20.7 | 31.7 | 43.2 | 55.7 | 69.2 | 84.0 | 100.3 | 118.4 | 138.4 | 160.5 |
| **4** | 12.5 | 25.3 | 38.5 | 52.3 | 67.0 | 82.8 | 99.9 | 118.5 | 138.8 | 161.1 | |
| **5** | 14.8 | 29.8 | 45.3 | 61.4 | 78.3 | 96.4 | 115.7 | 136.6 | 159.2 | | |
| **6** | 17.1 | 34.3 | 52.1 | 70.4 | 89.7 | 110.0 | | | | | |
| **7** | 19.3 | 38.9 | 58.8 | 79.5 | 101.0 | 123.5 | | | | | |
| **8** | 21.6 | 43.4 | 65.6 | 88.5 | 112.2 | | | | | | |
| **9** | 23.8 | 47.9 | 72.4 | 97.5 | 123.5 | | | | | | |
| **10** | 26.1 | 52.4 | 79.1 | 106.5 | 134.7 | | | | | | |
| **11** | 28.3 | 56.8 | 85.8 | 115.4 | | | | | | | |
| **12** | 30.5 | 61.3 | 92.5 | 124.3 | | | | | | | |
| **13** | 32.8 | 65.7 | 99.1 | 133.2 | | | | | | | |
| **14** | 35.0 | 70.2 | 105.8 | 142.1 | | | | | | | |
| **15** | 37.2 | 74.6 | 112.4 | 150.9 | | | | | | | |

| Continuous Power Rating including limitations of Traction Motor: | |
|---|---|
| Battery-Only Mode (3 batteries) 1 h discharge rate: | 47 kW |
| Hybrid Mode (IC engine/generator + 3 batteries): | 70 kW |
| Diesel Electric Mode (IC Engine/Generator only): | 70 kW |

Calculations performed for fully laden vehicle.

Highlighted areas NOT adjusted for any power required to operate auxiliaries (approx. average auxiliary power = 8 kW).

## Table 3
## Startability and Acceleration Calculations for the Multi-Mode Prototype Vehicle (with 3 batteries)

| **Drive Conditions and Vehicle Data** | | | **Startability and Acceleration from Rest** | | |
|---|---|---|---|---|---|
| # Passengers | Test Weight (kg) | Slope (%) | Calculations show that vehicle can start from rest? | Calculated time to accelerate to 20 km/h from rest (sec) | Calculated time to accelerate to 30 km/h from rest (sec) |
| 28 | 8,344 | 13 | NO | - | - |
| 15 | 7,460 | 13 | YES | 120 | 200 |
| 28 | 8,344 | 3 | YES | 7 | 10 |
| 15 | 7,460 | 3 | YES | 6 | 9 |
| 28 | 8,344 | 20 | NO | - | - |
| 28 | 8,344 | 1 | YES | 6 | 8 |

**Table 4**
**Multi-Mode Prototype Vehicle, Calculated vs. Targeted Performance**

| Performance Items* | Targets | From Calculations |
|---|---|---|
| Top Cruise Speed | ≥ 70 km/h / 43 mph | YES |
| Maximum Speed | ≥ 80 km/h / 50 mph | YES |
| Acceleration to 32 km/h | ≤ 10 sec | 12 sec (any drive mode) |
| Range: Battery-only | ≥ 60 km | YES |
| Range: Hybrid | ≥ 250 km | YES |
| Startability at 0 km/h | ≥ 20% grade | NO (slopes to 11% possible) |
| Gradeability at 35 km/h | ≥ 13% grade | Hybrid mode, short duration only |
| *Values given for maximum passenger loading and 1% grade unless otherwise specified | | |

Table 3 shows the calculated startability (the maximum grade that the vehicle can begin to move from rest) and calculated acceleration times from rest. These are highly dynamic conditions, affected by non-linear and transient effects, which were not accurately modeled. Despite this, startability and accelerations to approximately 30 km/h were taken to be independent of the drive mode (battery-only, engine/generator-only, or engine/generator + batteries) due to the characteristics of the electric traction motor at low speeds. This is because the power output from the electric motor linearly increases from 0 kW at 0 rpm, so at low speeds the batteries and/or the engine/generator can produce more power than the motor's maximum output power.

Acceleration times were calculated for the bus fully loaded (28 passengers) and moderately loaded (15 passengers) and compared to the initial performance targets, as shown in Table 3. The calculated times to accelerate to typical bus speeds under these conditions are acceptable for a bus application. A time of approximately 12 seconds would be required to accelerate to 32 km/h on a 1% grade for any drive mode, closely matching the target of 10 seconds specified in Table 4.

Startability was also calculated for a fully loaded bus (28 passengers) and moderately loaded bus (15 passengers), as shown in Table 3. Even up to the severe slopes of 13% found on the Quebec City route, startability was projected to be possible for a moderately loaded vehicle. The results indicated, however, that the startability performance target of 20% (Table 4) would not be met. Although it is unlikely that a real vehicle would ever encounter starting on such a grade, the 20% grade may reflect starting from a curb or pothole. As stated above, however, the calculations do not account for dynamic effects under these conditions.

To achieve the 20% startability target, the vehicle would have to be redesigned with gearing that results in a peak force output about 1.5 to 2 times higher than that used and/or an increase in torque from a redesigned motor.

**The gearing and motor design of the prototype vehicle was chosen to meet typical airport shuttle duty in which low speeds and slow accelerations would be the norm.** The system was not chosen specifically to meet high speeds and fast accelerations that may be encountered on freeway driving. For the vehicle to meet both a low-speed and high-speed duty, high-low gear shifting would be necessary. Preliminary investigations show that a 20% increase in gear ratio could be achieved in the available space of the prototype vehicle and at a low cost.

Although changes in gearing would be the primary method taken to extend the range of vehicle performance, changes to motor parameters or even doubling up on traction motors on the vehicle are other possible alternatives. Siemens has been involved in other hybrid electric bus projects in which twin motors were used. Clearly, the choice of one or two motors would be based on the intended purpose of the vehicle, exactly the point that is demonstrated by the multi-mode approach used in this project.

## 2.3 Vehicle Weight

An analysis of the prototype vehicle package and weight is shown in Table 5.

As with any vehicle, overall weight directly affects vehicle performance, including payload, braking, and fuel consumption. For electric or hybrid electric vehicles, reductions in overall weight (with corresponding increases in space, or more “weight space”) also affects the ability to increase the amount of on-board stored energy to further improve zero emission capability.

The project partners are considering future vehicle designs. For example, the weight of the bus structure can be reduced considerably through the greater use of aluminum in the vehicle structure.

## Table 5
## Vehicle Weight Distribution

| **Multi-Mode Hybrid Bus** | **Weight Analysis for 28 ft. Shuttle** | | |
|---|---|---|---|
| | # | **kg** | **lb.** |
| **Batteries** | | | |
| Z5C ZEBRA batteries | 3 | 591 | 1,303 |
| **Battery Fraction, Fb** (battery wt / loaded wt) | | **7.1%** | |
| **Payload** | | | |
| Maximum passengers (seated and standing) | 28 | 1,904 | 4,198 |
| **Payload Fraction, Fp** (payload / loaded wt) | | **22.8%** | |
| **Hybrid Drivetrain** | | | |
| Gas engine including radiator, exhaust, etc. | | 363 | 800 |
| Fuel tank plus fuel | | 204 | 450 |
| Siemens generator | | 120 | 265 |
| Engine adaptor | | 25 | 55 |
| Siemens Duo Inverter (1/2 for generator, 1/2 for traction motor) | 1 | 72 | 159 |
| Siemens traction motor | 1 | 120 | 265 |
| Speed reducer and brackets | | 68 | 150 |
| Cooling system for inverters, motor and generator | | 35 | 77 |
| Cables, harnesses, fuses, etc. | | 45 | 99 |
| Total Hybrid Drivetrain | | 1,052 | 2,319 |
| **Hybrid Fraction, Fh** (hybrid wt / loaded wt) | | **12.6%** | |
| **Vehicle Structure and Auxiliaries** | | | |
| Auxiliaries inverter | | 25 | 55 |
| On-board charger | | 25 | 55 |
| Roof-mounted heat pumps | 3 | 150 | 331 |
| Electric power steering & brake pump | | 35 | 77 |
| 12 V battery charger | | 5 | 11 |
| Axles, body, chassis, standard 12 V electrics, etc. | | 4,535 | 10,000 |
| Total Vehicle Structure | | **4,775** | **10,529** |
| **Vehicle Fraction, Fv** (structure wt / loaded wt) | | **57.4%** | |
| **TOTAL LOADED WEIGHT** | | **8,322** | **18,350** |
| | | | |
| **GVWR (by rating)** | | **8,617** | **19,000** |

## 2.4 CMVSS and FMVSS Issues

The vehicle developed for this project was based on modifications to an existing CMVSS-certified vehicle platform rather than a new, ground-up build, and used OEM equipment for most of the standard vehicle operations. This approach ensured that the prototype vehicle met all CMVSS requirements while being exempt from the need to demonstrate the requirements.

The increased GVWR of the prototype vehicle (8,617 kg; 19,000 lb.) from that of the base vehicle (7,255 kg; 16,000 lb.) was achieved solely through the use of increased rear tire size. The prototype vehicle, therefore, did not have to demonstrate new structural CMVSS requirements. In Canada, however, engineering reports of brake acceptability are not solely relied upon, so a physical brake test must be performed at the new GVWR.

Prior to the commercialization of this hybrid electric bus, a CMVSS compliance analysis will be provided to Transport Canada to clearly demonstrate that the bus meets or exceeds all safety requirements.

## 2.5 Physical Layout Issues

The key strategy during the development of the prototype multi-mode bus was to produce a useable vehicle where the payload fraction (i.e., ratio of maximum payload to GVWR) was in the region of 0.25. A purpose-designed vehicle clearly presented more design freedoms but it was not feasible for this project's short time horizon and constrained overall budget.

A self-imposed constraint was to only consider base vehicles, drive systems, batteries, auxiliaries, etc. that were already in low or medium volume production. The classic 40 ft. transit bus is made in relatively small quantities (e.g., 5,000/year in North America), but shuttles and delivery vans sharing similar vehicle structures sell in much larger numbers (e.g., >100,000/year). The cost structure of these vehicles is lower because they are built from high-volume components and the potential customer base is much larger. A 28 ft. shuttle would typically sell for less than Cdn$200,000. If special shuttles and vans can be provided with a hybrid powertrain at an acceptable price, then the potential for emissions reduction becomes widespread.

One arbitrary constraint was that the finished prototype hybrid shuttle could be sold for no more than twice the price of the standard diesel vehicle. This price is not commercially sustainable in the long term but it does discipline the project and point to the order of price reduction needed especially from the batteries, the drivetrain, and the auxiliaries.

A low-priority secondary objective was to bear in mind the future possibility of this vehicle concept being used for a fuel cell-battery hybrid. In principle this would involve replacing the engine/generator with the fuel cell system while retaining all other vehicle features.

This project thus had the primary objective of producing a vehicle that can serve as an overall technology demonstrator (hence the multi-mode features), but the lessons learned would indicate the direction for commercial viability, albeit initially in niche markets where price is not the only factor in the purchasing decision.

The key issue then became the feasibility of packaging a hybrid powertrain in a 28 ft. shuttle, and having done this, the key question became, “Is it a sensible, usable vehicle with significantly fewer emissions?” A hybrid powertrain for medium-size vehicles is often heavier than a diesel engine, and mechanical transmission and weight alone increase fuel consumption and hence emissions. The hybrid vehicle may thus start with a potential fuel consumption penalty for a particular duty and payload. In order to ensure a net benefit (i.e., a net reduction in emissions for comparable duty and payload), there have to be significant improvements in energy efficiency in the powertrain, in the operating strategies, in the auxiliaries and in the vehicle ratings.

## 2.6 Mechanical Drive Issues

### 2.6.1 IC Engine

From an emissions standpoint there is opposition to diesel fuel in urban areas. However, the diesel engine is well entrenched as a long-life power source with readily available cheap fuel. Natural gas has merit due to its reduced emissions, but infrastructure is an issue. Gasoline is normally regarded as cleaner than diesel but Otto cycle engines are not as energy efficient as diesel engines.

There is no clear winner and pragmatism entered into the decision for the prototype bus. Weight is the main enemy of all emissions reduction programs and so, particularly for a hybrid, it is desirable to reduce engine weight and size.

This project was very much a first approach to the multi-mode hybrid situation and there is virtue in the future at looking at other engines, such as even smaller diesel or gasoline/natural gas engines or clean burning micro turbines. The micro turbines have received a lot of support as a relatively clean source of primary power in areas such as California. They are available as 30 kW or 60 kW units and are more suitable for use at constant speed or limited range of speed (i.e., with the battery playing a larger role). With this philosophy, smaller industrial type diesel engines are also a possibility.

Since the objective was to stay as close as possible to the base OCC shuttle build, the engine choices were limited to those available from Ford and/or those physically compatible with the E 350 chassis. The final decision was to replace the normal 7.3 litre V8 diesel engine by a smaller Ford engine (5.4 litre V8) that could be run either on gasoline or natural gas. At low engine speeds the diesel clearly has more torque and hence more low-speed power. The real issue, however, was the match between the generator and the engine. The smaller engine was acceptable because the hybrid strategy involved power sharing and the engine power output was more than adequate for the generator chosen. The generator used has a rated peak output in the region of 100 kW at about 2,000 rpm matching well with the 5.4 litre engine, which has an output of about 90 kW at 2,000 rpm. The engine speed is increased for higher power, and at 3,000 rpm the engine and generator are both capable of approximately 135 kW. This means that a bus of the size of the prototype vehicle could operate without any power from the batteries if necessary. This is a good fault tolerance feature.

The 5.4 litre Ford engine is well proven, and the less arduous duty required during hybrid operation should result in good life characteristics for this application. The engine change (i.e., downsizing and changing from diesel to gasoline) resulted in a weight savings of 180 kg, which significantly contributed to the weight budget, making room for the electrical powertrain components.

The key engine characteristics of the 5.4 litre V8 gasoline/natural gas engine actually used in the multi-mode shuttle and the original 7.3 litre V8 diesel engine are shown in Figure 12 and Figure 13, respectively.

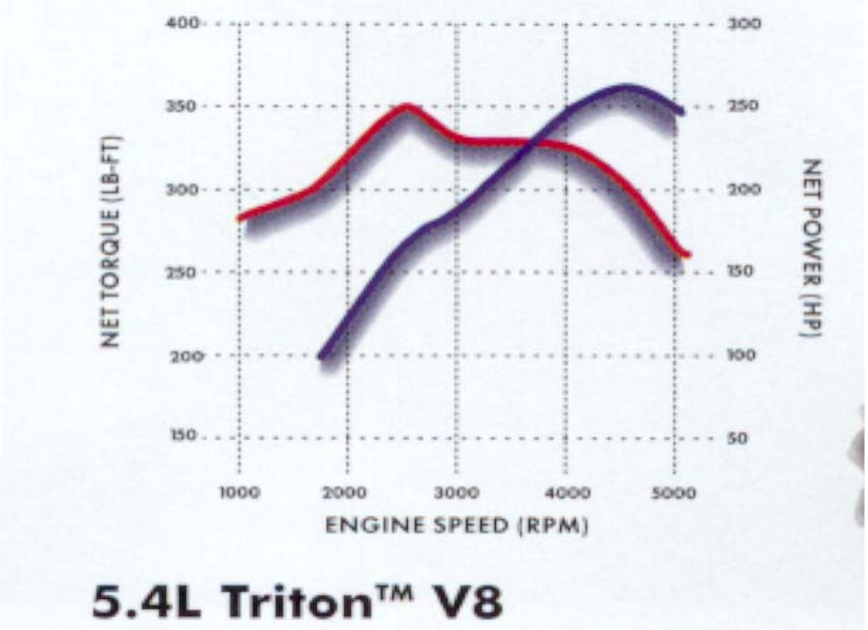


**Figure 12** **Ford 5.4 litre V8 gasoline/natural gas engine used in the prototype vehicle**

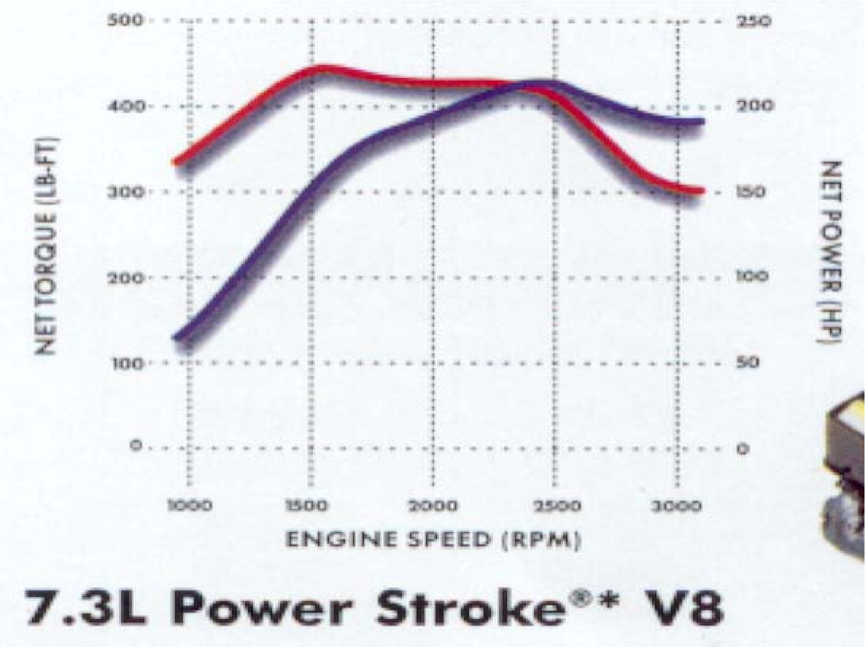


**Figure 13** **Ford 7.3 litre V8 diesel engine used in the base ELF vehicle**

### 2.6.2 Speed Reducer

The mechanical components that provide traction power to the wheels of the prototype vehicle are shown in Figure 3. The output shaft from the single traction motor is directly linked to a gear reducer. The gear reducer is a dual-chain system with a fixed gear reduction ratio of 2.6:1. The design of the gear reducer was developed by OCC since such a heavy-duty unit with the required gear ratio was not available on the commercial market. A drive shaft connects the output of the gear reducer to the front wheel drive axle. The differential gearing in the drive axle has a fixed gear reduction ratio of 5.13:1, creating an overall fixed gear reduction of 13.338:1 from the motor to the wheels.

As stated in Section 2.2, this gearing and motor design allows a reasonable low-end torque while achieving near-highway speeds. For example, the Siemens traction motor maintains its maximum torque from 0 rpm (0 km/h; 0 mph) to a speed of 3,000 rpm, equivalent to 33 km/h (20 mph). The near-maximum motor speed of 8,000 rpm is equivalent to a road speed of about 88 km/h (55 mph). This gearing and motor design of the prototype vehicle was chosen to meet typical airport shuttle duty in which low speeds and slow accelerations would be the norm. For the vehicle to meet both a low-speed and high-speed duty, high-low gear shifting would be necessary, but this was not implemented in the prototype vehicle.

## 2.7 Brakes and Suspension

The brake system of the base vehicle was left entirely intact for the multi-mode vehicle.

The hydraulic brakes are the same as the stock vehicle, powered by a hydraulic pump belt driven off the Ford engine. All four wheels have ABS, which was not altered from the base vehicle. A 12 V back-up system, which is part of the standard OEM system for brake pressure, senses loss of brake pressure regardless of hybrid or battery-only drive mode. Therefore, CMVSS certifications were not affected in any way.

Brake operation is identical to the IC engine vehicle whenever the engine is running. For driving in battery-only mode (engine/generator is not on) the brakes are run off a 1 HP electro-hydraulic pump, which runs off the installed 110 V auxiliaries inverter. The pump system is plumbed into the standard OEM power steering and power brake hydraulic system by means of lines, back-check valves, and pressure switches that activate when the OEM engine and generator are off. For driving in hybrid mode (engine/generator + batteries are operating), the 110 V electro-hydraulic pump acts as a supplement to the standard OEM hydraulic pump belt driven off the Ford engine. This approach allows battery energy to be conserved during engine-powered driving.

The brakes did not need to be enhanced when the GVWR was increased from 7,255 kg (16,000 lb.) to 8,617 kg (19,000 lb.) since the brake system is identical to that used by OCC on its conventional chassis up to 10,450 kg (23,000 lb.).

The front suspension system of the hybrid vehicle was not altered at all from that of the base vehicle. Changes to the rear suspension included the installation of a set of risers under the rear air bags to improve the ride at the rear of bus. The air suspension system on the rear axle still permitted either curbside or full rear-kneel for easier access, as developed by OCC for its paratransit vehicles. The air compressor for the rear suspension in the base OCC vehicle runs off the standard 12 V OEM system. For the prototype hybrid vehicle, the compressor was changed to allow connection to the 110 V auxiliary inverter. This reduced pump noise and reduced the overall current through the 12 V system. An electronic air suspension control system (ECAS) was also added on the rear suspension. This allowed a delay to be programmed in the reaction of the air bags to changes in vehicle height, thereby conserving air and requiring less operating time for the compressor.

## 2.8 Powertrain Cooling

The cooling system of the OEM engine is the same as that of any typical IC engine vehicle. It uses a water/glycol coolant circulated through the engine with an OEM heater/defrost system and heat exchanger that accesses the heat produced by the engine for heating of the vehicle’s internal body (i.e., during winter).

The Siemens motor, generator, and inverter are water-cooled. Since these devices operate at a lower temperature than the optimum operating temperature of the IC engine, a separate cooling system was required. A separate radiator, mounted in front of the standard OEM radiator, was used with its own electrical fan. Coolant circulates with the aid of an electrical booster pump through the motor, generator, and inverter as well as the inside body heat exchangers. In this way, heat produced by the electric powertrain may be utilized inside the vehicle or expelled in the front radiator.

The heating circuit of the electric powertrain cooling system is also plumbed into the OEM dashboard heating system for defrost and driver heating when the engine/generator is not running (i.e., zero emission operation).

The inverter used to power the auxiliaries is air-cooled, and was not part of the liquid cooling system.

## 2.9 Heating and Ventilation

Four separate systems are available to provide cab and passenger area heating.

Heating is supplied by conventional heat exchangers linked to the IC engine coolant.

Heating is also supplied by the electric drive system components (motor, generator, and inverters) through their own internal heat exchanger (and separate radiator), except at the dash where the system is connected to the standard OEM system.

In addition, there are three roof-mounted 110 V heat pumps operated from the 110 V on-board auxiliary inverter system. Each unit is capable of 5.1 kW (15,000 BTU) of either heating or air conditioning, and each unit may be operated individually or simultaneously for optimized performance.

The batteries themselves can also act as a reservoir of stored heat. The normal internal operating temperature of each battery is around 300°C, but excess heat can be generated during sustained high-power operation. To help keep the batteries within their operating temperature window, cooling fans are connected to each battery that circulate air from the passenger compartment through the battery. In the prototype bus, this air is exhausted directly outside of the vehicle. It is possible, however, to recuperate this heat to supplement the passenger area heating during cold climate conditions.

In typical bus duty applications, movement of passengers on and off the vehicle regularly occurs, making thermal management of the actual vehicle a complex issue. Efficiency of the heat pumps tends to decrease in cooler weather. In production, the ideal vehicle would have dual-paned windows to help retain heat. Such windows are expensive and heavy, and were not available to match the curved design of the current windows.

If required, especially during severe winter applications, a fuel-fired air heater can be easily installed to augment the heating system. This might only be required for battery-only drive since the standard OEM engine heating system can provide sufficient heating.

## 2.10 Vehicle Electrical System

The OEM vehicle 12 V electrical system, including that for the engine, dashboard controls, headlights, tail-lights, marker lights, turn signals, and safety booster pump for power brakes was not altered at all from the base vehicle for the hybrid vehicle. Therefore, all CMVSS certifications remained intact.

The 12 V systems on the hybrid vehicle operate off the 12 V OEM battery, which is charged from the 12 V alternator when the engine/generator is operating. During zero emission driving, the 12 V is acquired through the 110 V auxiliary inverter system.

Operation of the electrical system during zero emission, battery-only driving did not require new CMVSS certification since the certification focuses mainly on the positioning and strength of the electrical devices rather than their power source.

A pump for the power steering and power brake hydraulics, the three roof-mounted heat pumps, and the air compressor for the rear suspension were designed to operate off a 110 V AC supply. As part of the hybridization approach, one half of an air-cooled 2 x 70 kVA (nominal) dual-packaged inverter was chosen to control the supply to these auxiliaries. The inverter, associated filter box, and on-board transformer convert the load from the generator (through its inverter) or ZEBRA batteries to 110 V AC (nominal). The other half of the inverter is used during high power on-board charging.

A block diagram of the key components with electrical sources is shown in Figure 14.

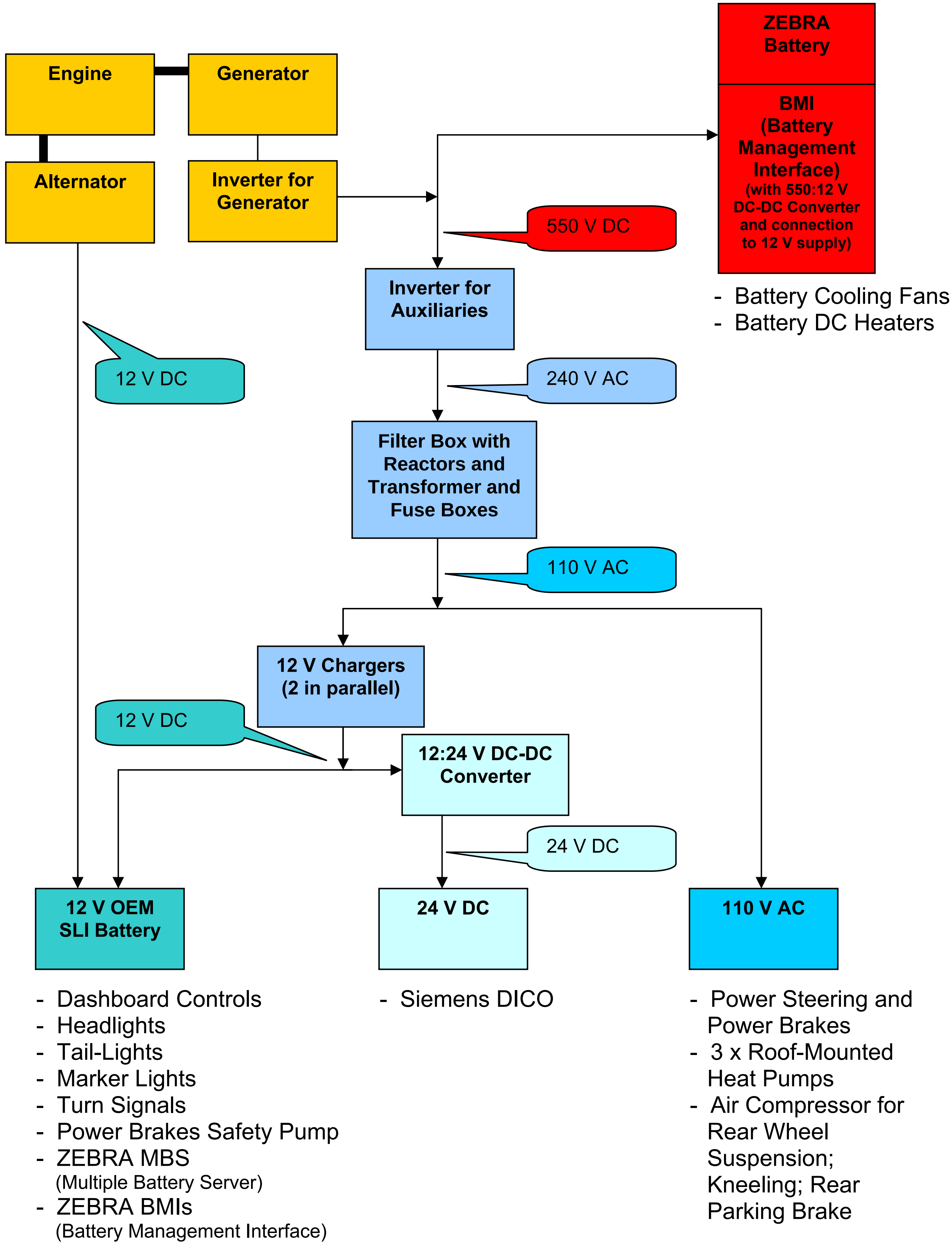


**Figure 14** **Vehicle electrical system**

## 2.11 Electric Drive

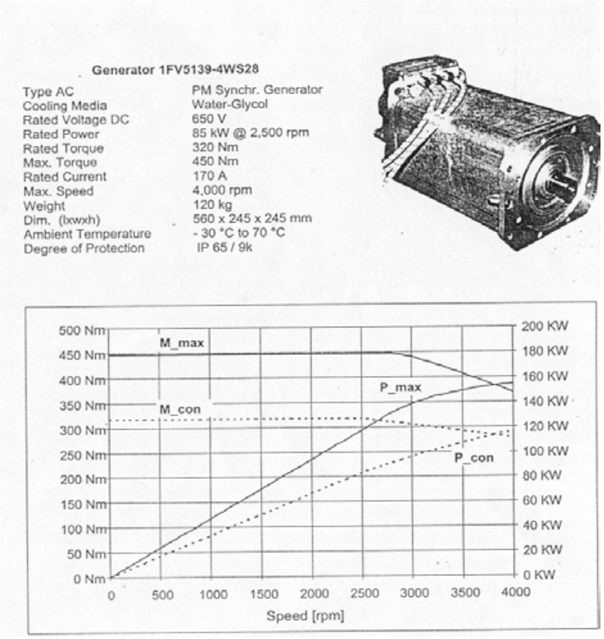
One aim of this project was to demonstrate operational capability for different driving modes while using components that were already commercially available. Therefore, standard Siemens drive components were chosen, with the components operating well within their capability for the duty required.

Descriptions of the major electric drive components are shown in Figure 15, Figure 16, and Figure 17. The ratings and power outputs need careful interpretation since they are dependent on actual battery load voltage and motor shaft speed. The trade-offs would be better if the battery voltage was higher to match the rated voltage of the electric drive components (e.g., in the region of 650 V rather than the ZEBRA battery's nominal voltage of 557 V). For example, predictions for gradeability have to make a number of assumptions relating to control algorithm design and the relationship between battery load voltage and generator output.

The large dynamic range of electric drives make it tempting to avoid gear shifting of any type. The consequence of this approach for the OCC shuttle was a high-speed (9,000 rpm) traction motor. At low road speeds (e.g., start-off on steep hills), the motor power available is limited by the gearing (i.e., the motor shaft speed). There was thus a compromise between top speed for highway purposes and gradeability to avoid larger or multiple traction motors. **The parameters of electric drive for the shuttle were arrived at based on normal airport shuttle use,** i.e., stop start on reasonably level ground with occasional use on freeways around the airport. **The design was not directly intended to meet the challenging Quebec City ÉcoloBus** route since it deliberately seeks out picturesque, steep, narrow roads with sharp, slow speed bends. Grades of up to 13% are encountered in the Quebec City route, while grades of up to 8% are encountered for more normal Canadian shuttle situations. Up to 90 km/h on flat roads is possible for the OCC shuttle with one traction motor.

For the OCC 28 ft. shuttle, the generator is arguably oversized for the one traction motor being used. If a heavier GVWR had been contemplated (e.g., 10 tonnes or more) then two traction motors would have been the better approach. The system is thus optimized for a slightly larger vehicle but the weight, size and cost penalties for the OCC shuttle are not large. For example, the dual-packaged inverter designs help save both weight and space.

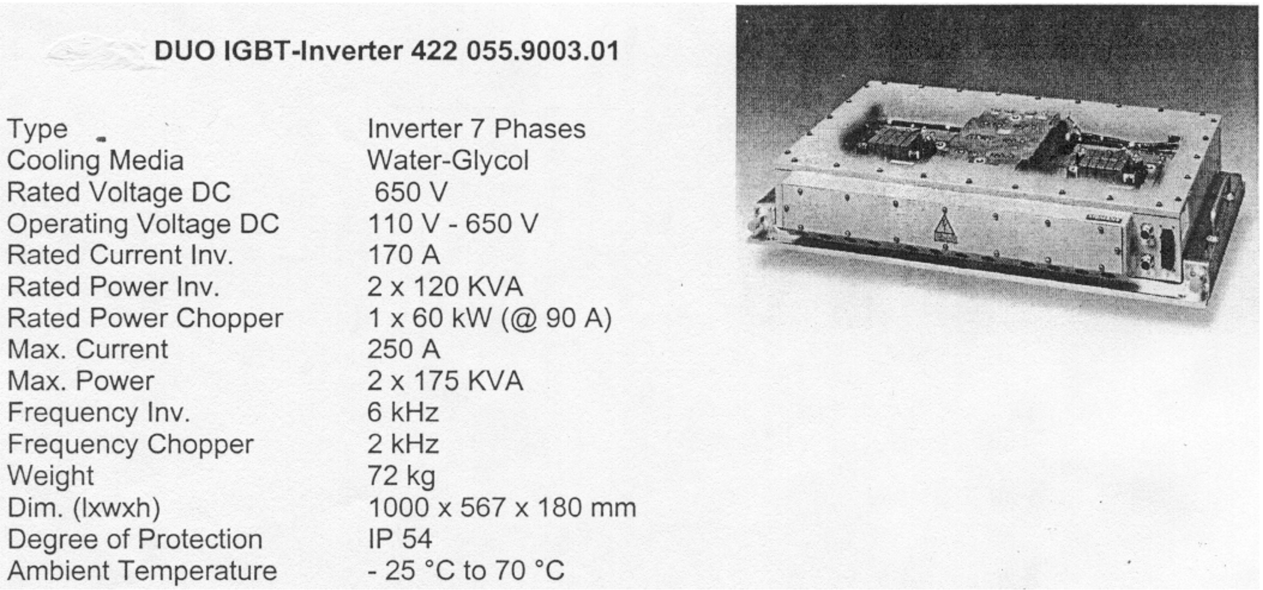
Real-world operating experience, such as actual operation on the Quebec City route, may well suggest changes to optimize items such as gearing, power-sharing control algorithms, and motor windings. Certainly a lighter weight vehicle structure would be a great help. In battery-only drive mode, three batteries should be enough to demonstrate capability, but it will not be sufficient for sensible extended pure EV operation, especially in Quebec City.



**Generator 1FV5139-4WS28**

| | |
|---|---|
| Type AC | PM Synchr. Generator |
| Cooling Media | Water-Glycol |
| Rated Voltage DC | 650 V |
| Rated Power | 85 kW @ 2,500 rpm |
| Rated Torque | 320 Nm |
| Max. Torque | 450 Nm |
| Rated Current | 170 A |
| Max. Speed | 4,000 rpm |
| Weight | 120 kg |
| Dim. (lxwxh) | 560 x 245 x 245 mm |
| Ambient Temperature | - 30 °C to 70 °C |
| Degree of Protection | IP 65 / 9k |

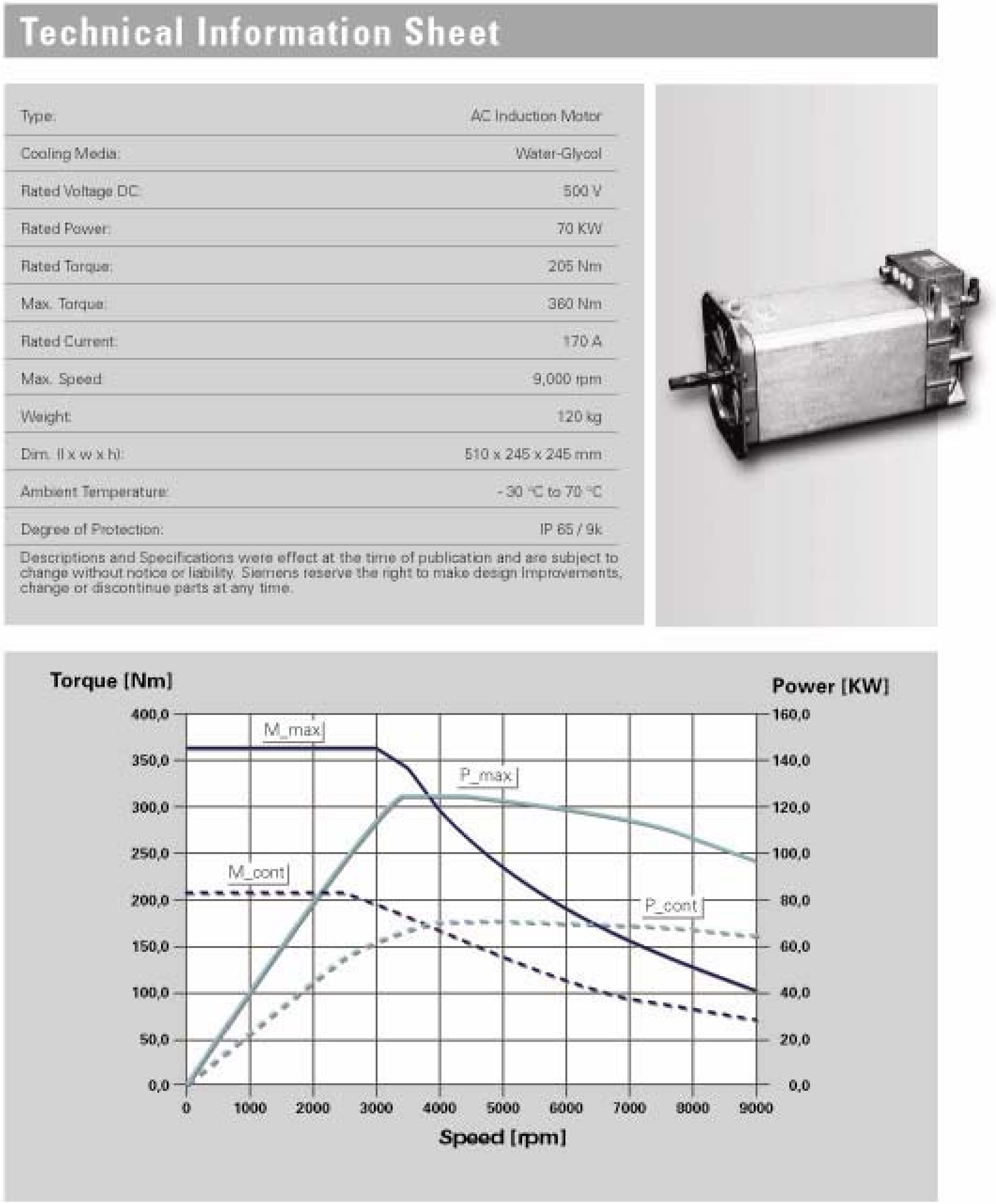
Figure 15 Power and torque curve for Siemens generator



**DUO IGBT-Inverter 422 055.9003.01**

| | |
|---|---|
| Type | Inverter 7 Phases |
| Cooling Media | Water-Glycol |
| Rated Voltage DC | 650 V |
| Operating Voltage DC | 110 V - 650 V |
| Rated Current Inv. | 170 A |
| Rated Power Inv. | 2 x 120 KVA |
| Rated Power Chopper | 1 x 60 kW (@ 90 A) |
| Max. Current | 250 A |
| Max. Power | 2 x 175 KVA |
| Frequency Inv. | 6 kHz |
| Frequency Chopper | 2 kHz |
| Weight | 72 kg |
| Dim. (lxwxh) | 1000 x 567 x 180 mm |
| Degree of Protection | IP 54 |
| Ambient Temperature | - 25 °C to 70 °C |

Figure 16 Specifications for Siemens dual-packaged inverter used for control of generator and traction motor



Technical Information Sheet

| | |
|---|---|
| Type: | AC Induction Motor |
| Cooling Media: | Water-Glycol |
| Rated Voltage DC: | 500 V |
| Rated Power: | 70 KW |
| Rated Torque: | 205 Nm |
| Max. Torque: | 360 Nm |
| Rated Current: | 170 A |
| Max. Speed: | 9,000 rpm |
| Weight: | 120 kg |
| Dim. (l x w x h): | 510 x 245 x 245 mm |
| Ambient Temperature: | - 30 °C to 70 °C |
| Degree of Protection: | IP 65 / 9k |

Descriptions and Specifications were effect at the time of publication and are subject to change without notice or liability. Siemens reserve the right to make design Improvements, change or discontinue parts at any time.

**Figure 17 Specifications for Siemens traction motor**

## 2.12 Control Systems

A schematic diagram of the signal communication and control system of the vehicle is shown in Figure 18.

The Siemens DICO (Digital Input COntrol unit) acts as the central control and communication link for all major vehicle drive components (e.g., inverters, motor, generator, battery MBS) based on inputs from the driver controls. The various operating mode parameters are programmed within the DICO using strategies pre-programmed by Siemens. The battery MBS (Multiple Battery Server) and BMIs (Battery Management Interfaces) directly control the ZEBRA battery system and were developed by MES-DEA. The MBS communicates with each of the battery BMIs and the DICO communicates with the MBS to ensure that battery performance and safety parameters are never exceeded. In this way, the DICO acts as the master control and controls the power sharing strategy between the batteries and engine/generator within the limits of the battery system for any given operating mode.

In the prototype vehicle, an on-board computer is available to select the operating mode and program the mode parameters, access and display any error codes stored by the DICO or MBS, and is used for data acquisition and storage during driving.

The Ford engine is controlled through a proportional/integral/derivative (PID) controller unit and linear actuator that were added on to the engine as part of the hybridization. Unlike a typical IC engine vehicle, the accelerator pedal is not directly connected to the engine throttle. Instead, a signal is sent to the DICO based on the accelerator pedal position. The DICO then sends a speed request to the PID controller based on the operating power sharing strategy. The linear actuator, which is mechanically connected to the throttle body in the engine, opens the throttle to the required position based on input from the PID controller. An engine speed feedback loop helps ensure adequate control over the engine speed.

The PID settings control the reaction time of the engine to the input speed signal as well as the initial overshoot and smoothness of the engine speed around the target speed. In the prototype vehicle, however, these parameters were not minimized to the extent hoped. This was because the PID settings must actually control and react to the entire actuator/throttle/engine combination, which is extremely complex.

During braking, the upper portion of travel of the brake pedal activates the regenerative braking system controlled through the DICO, while further application of the pedal activates the standard OEM hydraulic brake system. Charge generated during braking is controlled by battery system voltage, and is limited to a maximum of 670 V. The MBS continually monitors the battery status and reduces regenerative braking through the DICO to ensure charging parameters are not exceeded.

Controls and systems operated by the driver of the vehicle are all identical to the base vehicle, regardless of whether the vehicle is operating in engine/generator-only, battery-only, or hybrid drive. The standard OEM system found on any IC engine vehicle is used, so that the driver does not have to operate the vehicle any differently than “normal”.

This includes operation of the ignition, gear selector, accelerator and brake pedals, and steering.  For example, when the vehicle is stopped and the gear selector is placed in Park, the parking brake “air maxi” system on the brakes of the rear axle is automatically activated.  This is a normal 12 V operation.

If on-road vehicle operation should indicate that an additional gearshift is required to meet low-speed torque requirements as well as high-speed requirements, then a high-low gear changer would be required.  An overdrive button is already available as standard equipment on the vehicle, and the button could be altered to link to this type of gearshift.  In this way, “standard” IC engine operation of the vehicle would still be maintained.

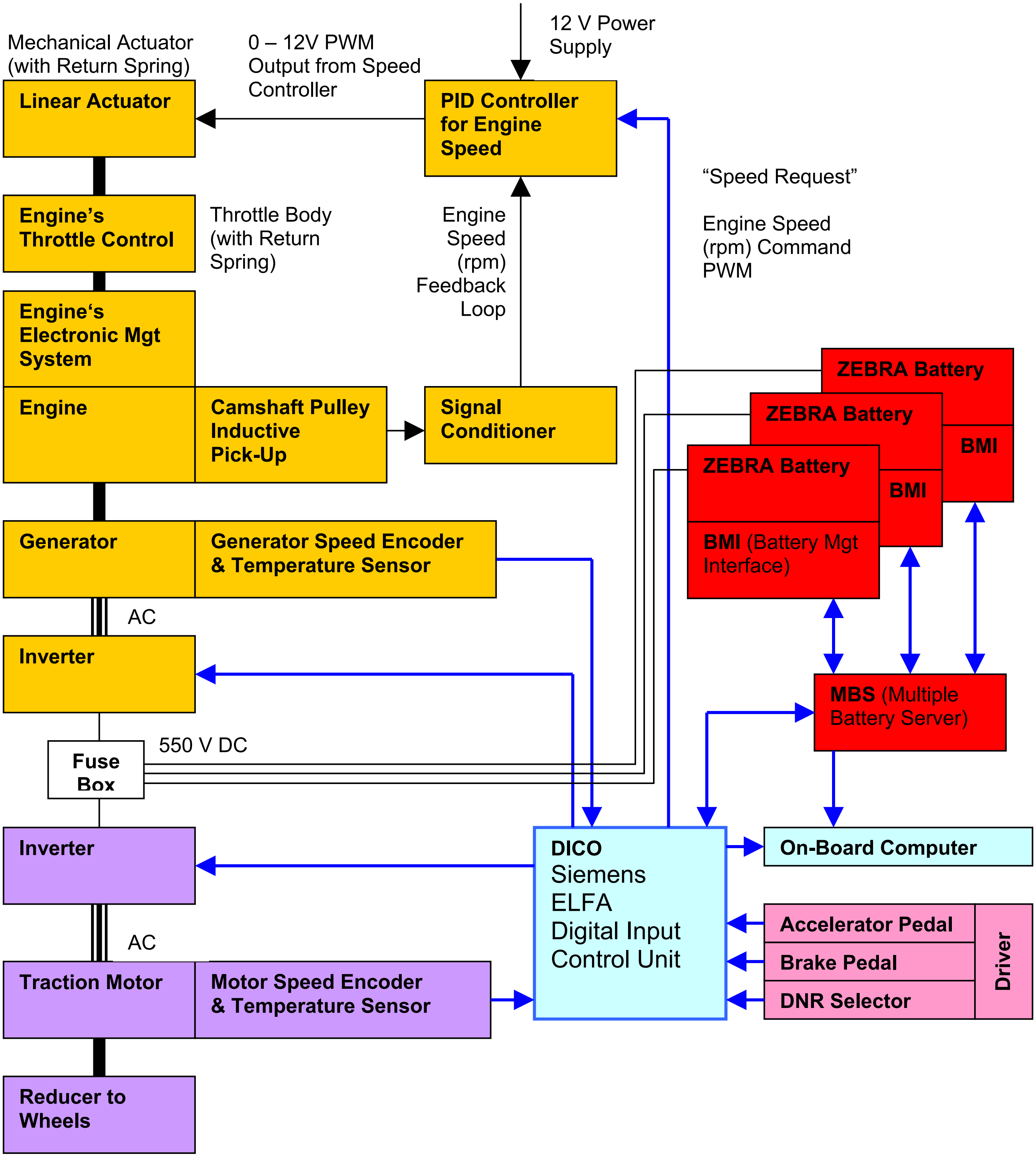


**Figure 18** Signal communication and vehicle control system

## 2.13 ZEBRA Batteries

The batteries chosen for the prototype OCC shuttle are ZEBRA batteries, manufactured by MES-DEA in Stabio, Switzerland. The chemistry of the batteries is sodium/metal-chloride.

Three Z5C ZEBRA batteries were placed on the OCC shuttle, with a nominal system voltage of 557 V. A description of the Z5C ZEBRA batteries used on the shuttle is shown in Figure 19, and a photo of the installation of one battery inside the bus is shown in Figure 4. The Z5C batteries on the OCC bus comprise 216 individual 2.58 V, 32 Ah cells connected in a single string to produce the nominal 557 V, 32 Ah battery. Each 557 V ZEBRA Z5C battery weighs approximately 197 kg and is capable of 17.8 kWh, 32 kW. These figures are equivalent to 90 Wh/kg and 160 W/kg.

Each ZEBRA battery unit has an electronic controller and contactor as an integral part of the container, called the BMI (Battery Management Interface). Each BMI controls the SOC and charge and discharge processes of the battery, and the communication with other parallel batteries and the vehicle drive unit.

A controller, called the MBS (Multiple Battery Server) controls the network of parallel batteries, including the charge of the battery network, as well as the on-board data acquisition.

The ability for ZEBRA batteries to be connected in parallel is a unique and valuable system design feature. For example, for improved "charge-depleting" performance (i.e., reduced emission range in hybrid mode, or increased zero emission range in battery-only mode), as much as 70 kWh could be placed on the multi-mode bus and still be within the GVWR. For the same shuttle designed as a pure electric vehicle (EV) without an engine/generator (also called a "grid-battery hybrid"), 125 kWh could be used within the same GVWR to give even greater zero emission range. Cost per kilowatt-hour of the batteries at this point is a limiting factor.

Most batteries have an operating window of less than 50°C, but ZEBRA has a window double this amount. ZEBRA operates typically above 260°C and so the combination of the thermal capacity, the insulation, and the $\Delta T$ means that the battery can also efficiently take in, store and deliver thermal energy independently of the chemical reactions generating electricity.

This heat can be used for vehicle heating, such as windshield clearing or space heating. The retrievable stored heat is approximately 10% of the nominal electrical stored energy (e.g., a Z5C has a nominal rating of 18 kWh with an additional thermal storage of 1.8 kWh).

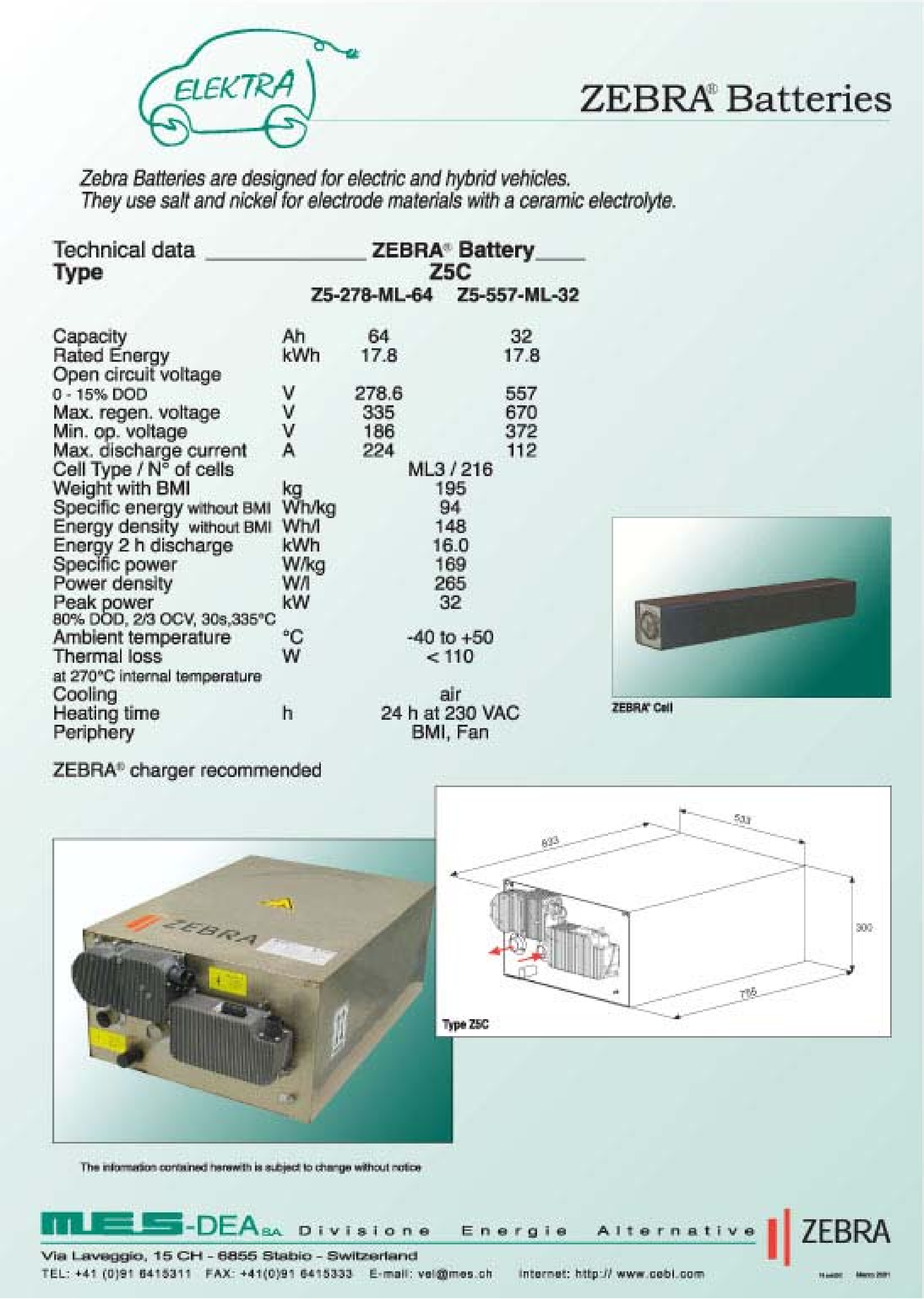
ZEBRA thus has major advantages for bus hybrids aiming for large emissions reductions, the only disadvantage being the need to plug it into the electrical grid overnight for thermal and SOC balancing and automatic SOC calibration.

An important aspect of battery choice is the consideration for safety. Batteries, like other energy storage devices, are capable of releasing energy in undesirable ways, such as heat, toxic emissions or, in extreme circumstances, small explosions. The ZEBRA battery, with its benign chemistry combined with strong steel packaging and excellent thermal management, is perhaps the most desirable of all batteries from this aspect.

The sodium sulfur battery, which had a similar construction to the ZEBRA battery (i.e., ceramic electrolyte with molten salt) had thermal runaway mechanisms with a potential for fire. The chemistry of the ZEBRA battery, however, does not support thermal runaway mechanisms and even under disaster scenarios the emissions would not make the situation any worse.

The nickel/metal hydride (NiMH) battery in the liquid cooled configuration could have been used in the OCC shuttle, but the lower specific energy density (about half that of ZEBRA at a system level) and the larger size would have been limiting factors. The NiMH would need chilled water for cooling in hot climates and water heaters for cold climate work, and there is still a necessity to plug in overnight. Heating would not be a problem with engine-based hybrids or with a continuously operating fuel cell because of the waste heat generation. The provision of adequate quantities of chilled water is a bigger issue particularly for charge-depleting strategies.

The only other short-term battery option considered was lead acid. This would be a low cost system, but only if the issues of thermal management are ignored. Maintaining SOC balance in a 550 V string is difficult and requires sophisticated electronics, almost certainly using bypass systems for selective charge/discharge of modules. Also, the low specific energy density of lead acid (e.g., 30% of ZEBRA) limits energy interchange, although the short-term power assist is quite good (50 kW to 80 kW should be quite possible). A “charge-maintaining” hybrid is the only practical operating strategy. In this type of strategy, there is relatively little stored battery energy available, there is limited energy exchange into and out of the battery system, the engine (or fuel cell) is the vehicle’s main energy source, and the engine maintains the battery pack in a relatively narrow range of SOC. Such vehicles could be operated without being plugged into the grid. Lead acid would not be a good choice for a multi-mode hybrid with the requirement for significant energy exchange. It is also very difficult to adequately thermally manage a large-area lead acid battery, and module balance is always an issue. The weight of a battery of adequate kWh is also an important issue (equivalent to about 30 passengers).



## ZEBRA® Batteries

*Zebra Batteries are designed for electric and hybrid vehicles.*
*They use salt and nickel for electrode materials with a ceramic electrolyte.*

| Technical data<br>**Type** | | **ZEBRA® Battery**<br>**Z5C**<br>**Z5-278-ML-64** | <br><br>**Z5-557-ML-32** |
|---|---|---|---|
| Capacity | Ah | 64 | 32 |
| Rated Energy | kWh | 17.8 | 17.8 |
| Open circuit voltage<br>0 - 15% DOD | V | 278.6 | 557 |
| Max. regen. voltage | V | 335 | 670 |
| Min. op. voltage | V | 186 | 372 |
| Max. discharge current | A | 224 | 112 |
| Cell Type / N° of cells | | ML3 / 216 | |
| Weight with BMI | kg | 195 | |
| Specific energy without BMI | Wh/kg | 94 | |
| Energy density without BMI | Wh/l | 148 | |
| Energy 2 h discharge | kWh | 16.0 | |
| Specific power | W/kg | 169 | |
| Power density | W/l | 265 | |
| Peak power<br>80% DOD, 2/3 OCV, 30s,335°C | kW | 32 | |
| Ambient temperature | °C | -40 to +50 | |
| Thermal loss<br>at 270°C internal temperature | W | < 110 | |
| Cooling | | air | |
| Heating time | h | 24 h at 230 VAC | |
| Periphery | | BMI, Fan | |

ZEBRA® charger recommended

ZEBRA® Cell

The information contained herewith is subject to change without notice

MES-DEA SA Divisione Energie Alternative ZEBRA
Via Laveggio, 15 CH - 6855 Stabio - Switzerland
TEL: +41 (0)91 6415311 FAX: +41(0)91 6415333 E-mail: vel@mes.ch internet: http:// www.cebi.com

Figure 19 Description of ZEBRA batteries used in prototype shuttle

### 2.14 Batteries and Charge Management

The ZEBRA battery has many advantages, but one of the disadvantages is that it needs to be connected to the electrical grid, ideally every night. This is for the purpose of thermal and SOC balancing/calibration. This is a low-power automatic operation usually accompanying the other charging procedures.

As a charge-maintaining hybrid in an ideal scenario, the battery should never need to be connected to the grid, and certainly other hybrid systems have been developed with other types of batteries that attempt to operate this way. For grid-battery hybrid (i.e., pure EV) or charge-depleting strategies, starting the working day at top of charge is desirable anyway since more energy is available for power sharing, zero emission waiting, or start-offs.

Some transit operators or users of shuttles find it acceptable to connect to the grid overnight, particularly if the overriding issue is to maximize the reduction of emissions. On the other hand, transit authorities with large and complex operations find overnight connection to the grid an impractical and unacceptable operations procedure.

At this stage of the technology, “no plug hybrids” probably means that users have to be content with lead acid systems, tolerate lost operation time for periodic maintenance, and accept shorter battery life. This policy will also limit the amount of emissions reduction per vehicle. However, if their present fleet is old and a heavy polluter, then a limited emissions reduction strategy probably makes sense until the vehicles need replacing again. This pragmatic approach results in progress being made without too much disruption to the operations schedule. Many transit operators would sympathize with this approach.

The OCC shuttle team has more ambitious objectives in relation to emissions reduction. The objective is to push the technology envelope with niche market vehicles. The experience and lessons learned can later be applied more broadly to other vehicle applications.

The benefits of ZEBRA batteries can thus only be utilized in situations where it is acceptable to connect to the grid overnight. The issue then becomes, “Should the charging system be on-board or off-board?”

In general, buses with 600 V batteries need charging voltages that can approach 700 V. For the prototype bus, the nominal 550 V batteries can reach voltages near 580 V during overnight charging and voltages near 620 V during fast charging. Off-board chargers would have to provide a DC connection with safe contactors and connections at these voltage levels. This is not a trivial task. It is expensive, and it raises safety issues, particularly for outdoor situations.

The most desirable scenario is for the main high-voltage charger to be on board with the minimum of infrastructure off-board. The OCC multi-mode demonstration bus has two different on-board charging systems, one for low-power charging and one for high-power charging. Block diagrams of the key components with the electrical source for each system are shown in Figure 20 and Figure 21.

For slow, or overnight charging, the system used comprises three individual 3.2 kW chargers installed on the bus, one for each battery. These chargers were supplied by MES-DEA, the manufacturers of the ZEBRA batteries. The off-board infrastructure for low-power charge is simply a 240 V, single-phase AC supply.

For fast, or interim high-power charging from the grid, the system used comprises one half of a duo inverter rated at 70 kVA configured by BET as an on-board charger with a power feed of 380 V, 3-phase AC. The off-board infrastructure for high-power charge, shown in Figure 22, is thus very simple and low cost. It is composed of a single box containing the required transformers, filters, fuses, and connectors with breakers. The connection from the off-board system is at a more normal 3-phase AC voltage for which the components (i.e., contactors, fuses, etc.) are readily available and relatively low cost.

This is an important issue; otherwise, large electric vehicles with high-voltage batteries would always need expensive off-board chargers and connections. This would limit the areas where they could be sensibly used. It is very easy to sympathize with transit operators who, when faced with the possibility of expensive off-board chargers for their 550 V lead acid batteries, wish to avoid off-board charging completely.

For a charge-maintaining strategy, the battery would receive charge from the grid only overnight for thermal balancing and SOC balancing/calibration. In this strategy, one half of the duo inverter configured as an on-board high-power charger is redundant.

In charge-depleting or grid-battery hybrid strategy the battery may receive charge at either of the following times:

- during the day from the high power charger (the ½ duo inverter)
- overnight from the low power individual chargers

The charger inverter and the ZEBRA control system make the weight penalty (approximately 25 kg for on-board fast charging) well worthwhile. The OCC shuttle can thus operate anywhere with very simple, inexpensive, lower AC voltage off-board infrastructure for fast charge, while connection to the grid for overnight slow charging is also not a major concern.

The charge status of the network of ZEBRA batteries is monitored by the MBS, which is provided by MES-DEA when multiple batteries are connected in parallel. The MBS is capable of controlling up to 16 ZEBRA batteries in parallel. An electronic controller - the BMI - controls the battery charge and discharge processes. The BMI and contactor are integrated into the front of each individual battery.

The charge control algorithms are predominantly constant voltage. The normal (slow, overnight) charge rate through each 3.2 kW charger is rated at 2.67 V/cell, or a maximum of approximately 6 A. At approximately 90% SOC the charge current is reduced until 100% SOC is reached. This means that the battery network on the OCC shuttle (32 Ah per battery; 96 Ah total) requires approximately 6 to 8 hours to completely charge from 0% to 100% SOC.

The BMI, in conjunction with each individual battery charger, brings the batteries to 100% SOC, balances them thermally by means of the battery's internal heater or cooler, and resets the SOC algorithm. SOC monitoring during the working day is a straight integration process since for the ZEBRA battery: Ah OUT = Ah IN.

The high-power interim charge rate through the charger inverter using supply from the grid and off-board infrastructure is limited to about 30 A per battery, or 2.85 V/cell. This high-power charge rate is limited by the BMI to no more than 80% SOC. The battery network on the OCC shuttle (32 Ah per battery; 96 Ah total) would require about 1 hour to completely charge from 0% to 80% SOC from the grid. A 15-minute fast charge would replace approximately 20% of the on-board energy.

Since the high-power charge rate cannot be applied above 80% SOC, the charge rate must be reduced above this point. For daytime, or fast interim charging, therefore, the SOC would likely not go above 80%. The current per battery will not normally exceed 30 A and so interim charging will normally be at less than the 1 hour rate.

Based on rough estimates for fleet operations, a battery could consume up to 1.5 times its nameplate energy in a working day of ten hours. Approximately 0.5 of the nameplate energy would therefore need to be replaced from the grid in a grid-battery hybrid scenario. A sensible strategy that meets these needs and that could be accommodated by fleet operations would be three interim charges at the 2 hour rate (15 A/battery) for 20 minutes every 3 hours during normal breaks, (e.g., layovers, meal breaks, etc.). Other strategies are of course possible.

Regenerative braking is normally allowed when the SOC falls below 75% to 80% and is limited by each BMI to 60 A/battery, and 3.1 V/cell. The cut off above 80% SOC is gradual to avoid safety issues. In a charge-maintaining hybrid strategy the SOC is normally managed between 75% SOC and 45% SOC, and so the capability for regenerative braking is quite good. Furthermore, higher kWh ZEBRA batteries are normally only used for large vehicle hybrids where higher energy interchange is required to reduce emissions, and so there is an inherent capability to capture larger amounts of regenerative energy because the permissible SOC swing encompasses more kWh.

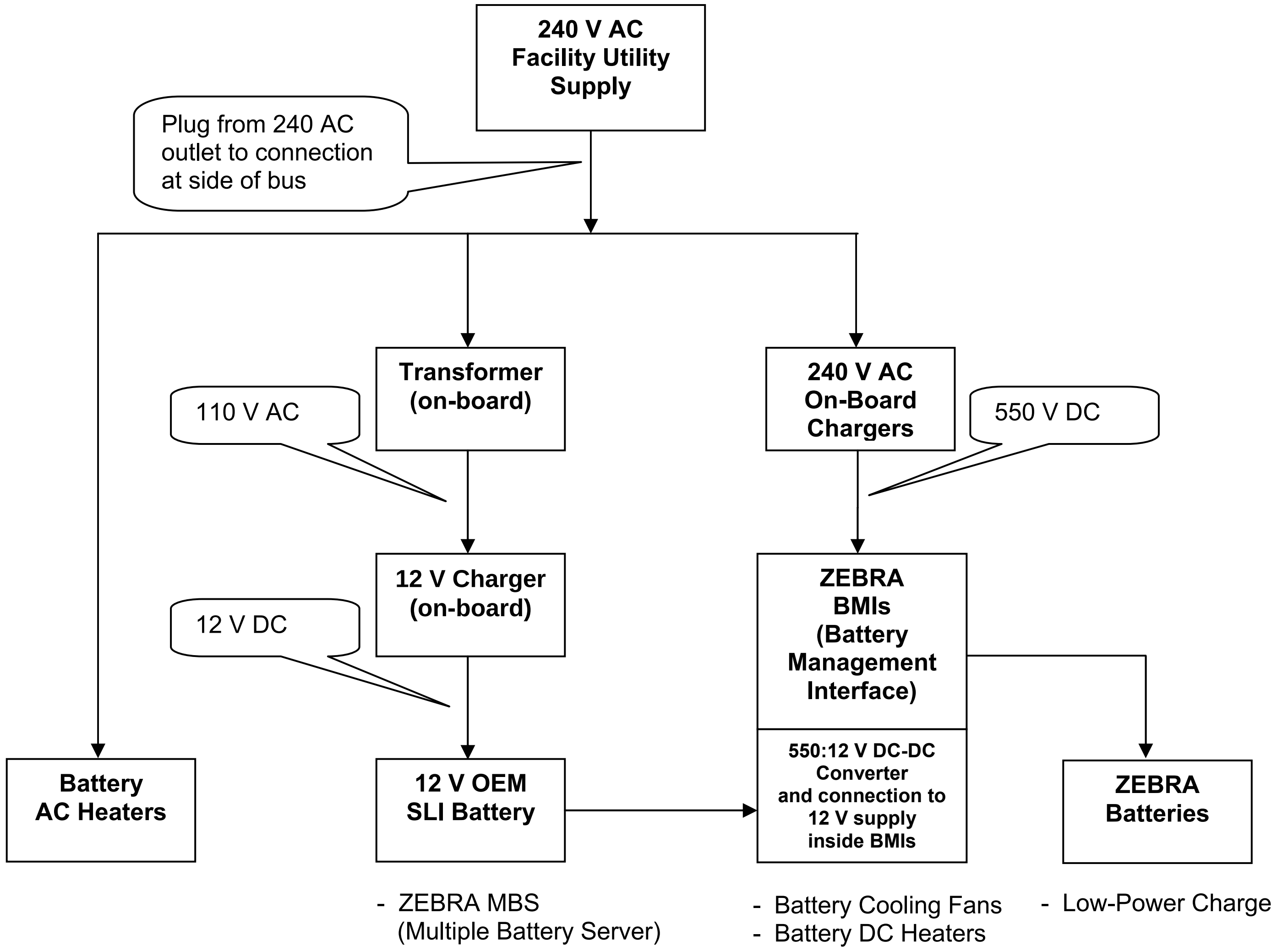


**Figure 20** Vehicle electrical system for low-power charging

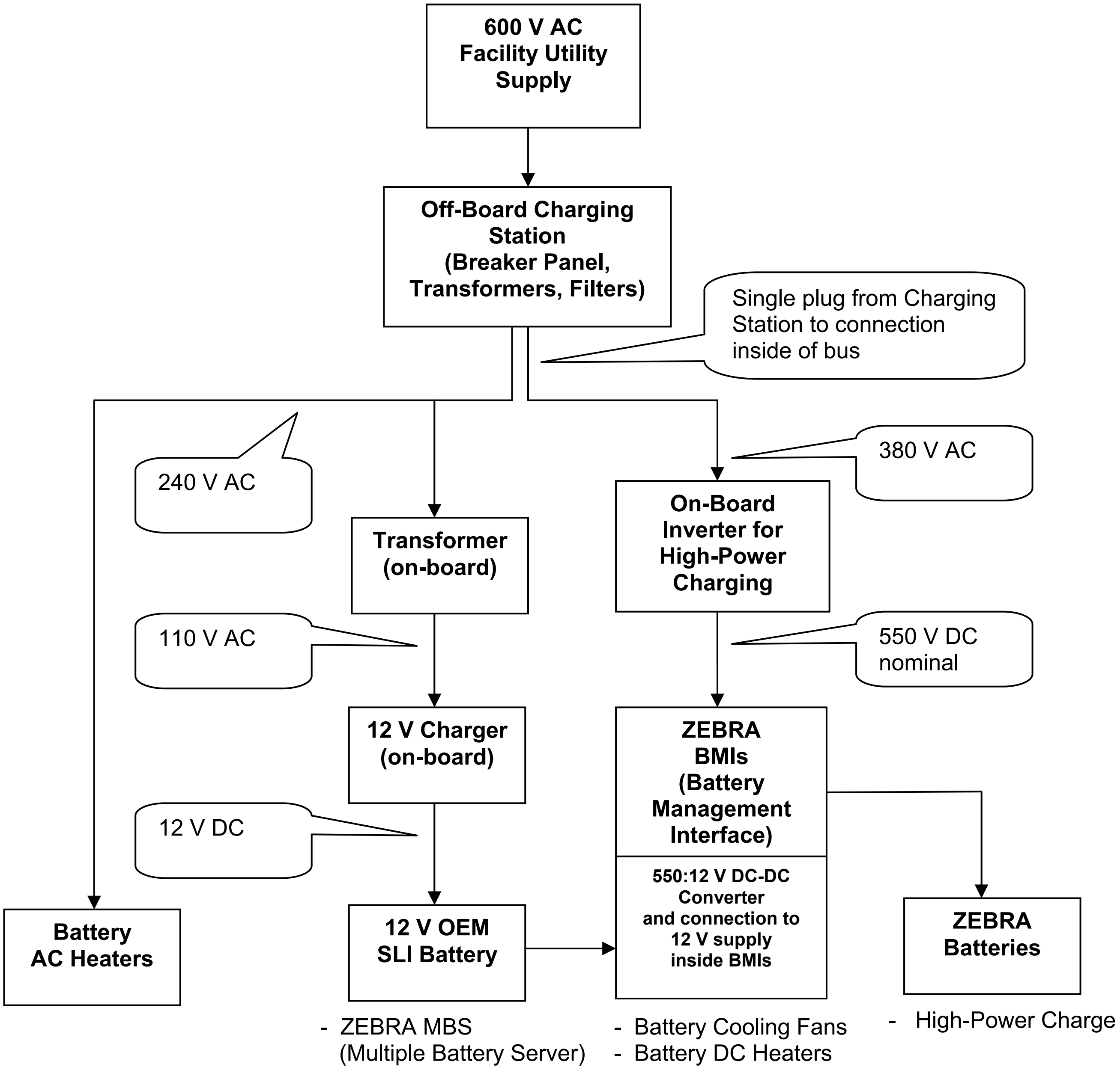


Figure 21 Vehicle electrical system for high-power charging

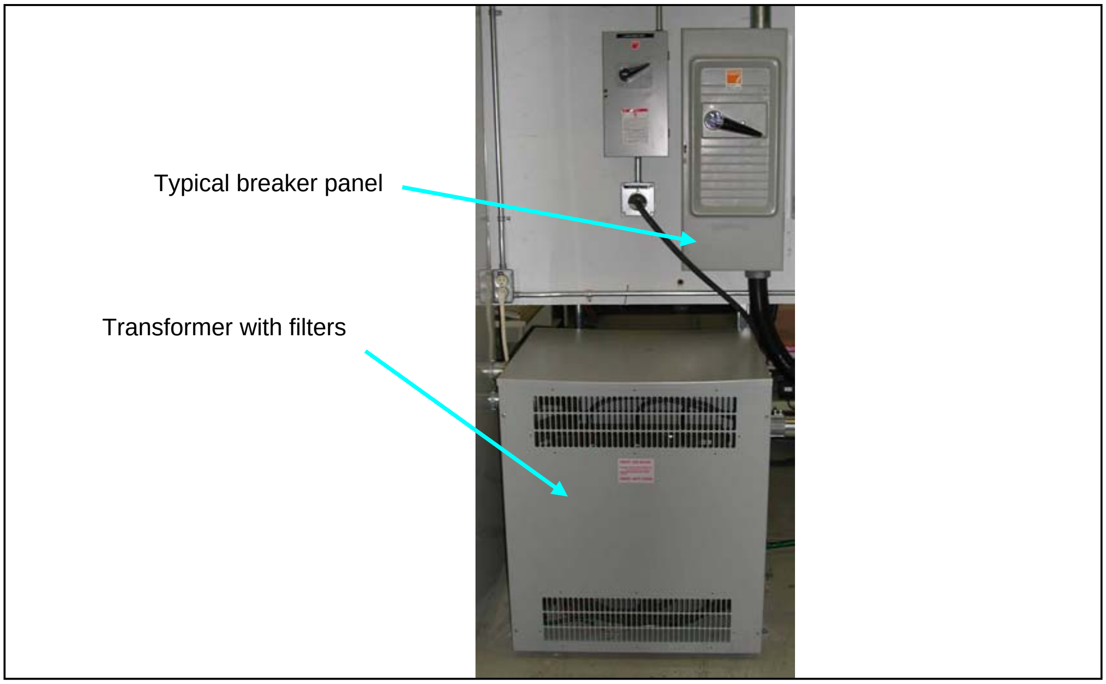


**Figure 22 Example of low-cost, lightweight off-board infrastructure for 70 kVA high-power fast charging.** Photo shows standard wall-mounted breaker panel connected to single box containing applicable transformers, filters, connectors, fuses, etc.

## 2.15 Auxiliaries

As described in Section 2.10 and Figure 14, the OEM vehicle 12 V electrical system controls most of the vehicle auxiliaries, including the dashboard controls, headlights, tail-lights, marker lights, turn signals, and safety booster pump for power brakes.

An electro-hydraulic pump for the power steering and power brakes, the three roof-mounted heat pumps, and the air compressor for the rear suspension operate off a 110 V AC supply. One half of an air-cooled 2 x 70 kVA (nominal) dual-packaged inverter controls the supply to these auxiliaries. The inverter, associated filter box, and on-board transformer convert the load from the generator (through its inverter) or ZEBRA batteries to 110 V AC (nominal). The other half of the inverter is used during high-power on-board charging.

The pump for the power steering and power brakes, heat pumps, and suspension air compressor are single-phase 110 V loads and these are spread across the 3 phases of the auxiliaries inverter output. The inverter has a high-frequency component and voltage spikes. In order to avoid damage to the small drive motors (such as on the various pumps) a sinusoidal filter was also installed. The inverter unit on the prototype vehicle is more sophisticated and over-rated than is really needed, and it is heavy (33.2 kg) due to the current rating. In the future, this issue can be addressed possibly in association with an optimized auxiliaries inverter.

Typical auxiliary power consumption is approximately 8 to 10 kW when the heat pumps are in use. In battery-only mode, the allowable power to the motor was electronically limited to 10 kW below the maximum output of the three ZEBRA batteries to ensure that auxiliary power was always available. In the future, this limitation can be overcome with a more intelligent control strategy or by increasing the number of ZEBRA batteries.

A description of the control used for auxiliaries for the OCC prototype bus compared to other vehicle systems, along with weight comparisons is shown in Table 6.

## Table 6
## Control of Vehicle Auxiliaries and Weight Comparison

| Item | E350 Base Vehicle Mechanical Drives (kg) | Siemens Aux. Motor Mechanical Drives (kg) | OCC Multi-Mode Electrical Drives (kg) | KW or kVA Rating |
|---|---|---|---|---|
| Pump for Power Steering/Power Brakes | 10 | 10 | 30 | 1.6 (1 phase) |
| Air Conditioner Unit (E350) | 150 | - | - | |
| Heat Pumps (Heating and Cooling) x 3 | - | 150 | 150 | 6.0 (3 units, 1 phase) |
| 12 V Battery Charger - Rotating Machine | 15 | 15 | - | |
| 12 V Battery Charger - Inverter | - | - | 2 | 2.0 (1 kW/kg, 1 phase) |
| Pump for Siemens Cooling Water | - | 2 | 2 | |
| Auxiliary Motor - Siemens Induction Motor | - | 54 | - | 20 (650 V AC) |
| Inverter – ½ “Duo” for Auxiliary Motor | - | 36 | - | |
| Pulleys, Belts, and Brackets | 20 | 20 | - | |
| Inverter – ½ “Duo” Siemens for 110 V AC | - | - | 36 | 120 (> 2 kW/kg) |
| DC/DC Converter (24 V supply to inverters) | - | - | 4 | 0.24 |
| Sinusoidal Filter for 110 V AC supply | - | - | 33 | 14 (2 units) |
| **Total Weight: E350** | **195** | | | |
| **Total Weight: Siemens Aux. Motor Drive** | | **287** | | |
| **Total Weight: OCC Electric Drives** | | | **257** | |
| **Maximum Power: OCC Electric Drives** | | | | **10** |

## 2.16 Power and Energy Requirements

For hybrid electric operation, power and energy requirements should be optimized toward reduced emissions as well as reduced energy consumption. In the prototype multi-mode vehicle, however, the 5.4 litre Ford engine was used only because of availability issues. A much smaller engine should have been used. Therefore, the requirements for the prototype vehicle focused on reduced energy consumption.

Simplistically, the more energy delivered by the battery, the bigger the emissions reduction. This is clearly the case for charge-depleting strategies, but it is more complex for charge-maintaining scenarios since all of the energy has to come from the engine anyway. The engine management strategy clearly is an issue, but generally, the more energy that the battery can take in while the engine is in its most efficient operating mode for later delivery when the engine is not running or is in a less efficient mode, the better. The battery can also be used for power sharing to avoid or reduce engine power peaks. It is obviously desirable to operate in the trough of the specific fuel consumption curve of the engine to minimize the grams of fuel consumed per kilowatt-hour of energy produced by the engine.

The driving pattern is an important factor and so there is no unique answer to the question, “How many kilowatt-hours is enough?”. The duty cycle initially targeted for the development of the electric drive for the shuttle was based on normal airport shuttle use, which is less dynamic and energy demanding than the CBD + Arterial cycle. Although the design was not intended to meet the Quebec City ÉcoloBus route requirements, this represents an extreme end of one possible duty cycle and driving pattern.

For small vehicles, power sharing, weight and cost/kilowatt are the important issues. For many small hybrid electric vehicles currently in operation, the power delivery to the wheels is primarily mechanical from the engine and transmission, and the battery is used merely for assist to help optimize fuel consumption. The stored energy of the batteries for these systems is quite small (e.g., approximately 2 kWh) as is the energy interchange. The power characteristic of the battery is the main design criterion. Power to energy ratios of >15 are desirable (e.g., for >30 kW), and NiMH is currently the battery of choice.

For larger vehicles such as buses the energy interchange is much higher (e.g., by a factor of about 30 to 40). This is due to higher regenerative braking (more stop-starts), the desire to prevent idling and for the initial acceleration from rest to be electric, and of course the higher vehicle weight (e.g., factor 10). The power-sharing ratio is probably only two to three times that of a small vehicle but it must be sustained for longer periods (i.e., a further requirement for more stored energy). The ZEBRA battery has a power-to-energy ratio of about 2, which would not produce a good small vehicle hybrid battery. However, the superior specific energy density (typically twice that of NiCd batteries at the system level) allows higher stored energy and thus makes it a good choice for large vehicle charge-maintaining hybrids. For charge-depleting hybrids the benefits of the higher specific energy density are even more important.

The degree of emissions improvement depends on the hybrid strategy and, clearly, the more zero emission driving the better. The charge-depleting strategies are superior for reducing emissions but there are vehicle operational issues such as range and opportunities for recharge. The more difficult issue is the improvement that is possible in the charge-maintaining scenario. The vehicle weight is a major factor particularly for an all steel vehicle.

Table 7 shows of the power and energy balance of the prototype 28 ft. OCC shuttle bus. The values show the approximate performance of the vehicle when operated in different drive modes: battery-only drive (EV mode); engine/generator-only drive (no batteries, termed diesel-electric mode); engine/generator + batteries drive (hybrid mode). The values are based on the actual vehicle system design, including the limitations of the traction motor (i.e., Siemens generator coupled to a 5.4 litre V8 Ford engine; three Z5C ZEBRA air-cooled batteries; one Siemens AC induction drive motor).

**Table 7**
**Available Power and Energy in Different Drive Modes**

| Shuttle Drive Mode | Maximum Power | Maximum Continuous Power | Useable Energy |
|---|---|---|---|
| Batteries Only | 96 kW | 47 kW | 48 kWh |
| Engine/Generator Only | 120 kW | 70 kW | 38 US gallons |
| Engine/Generator + Batteries | 120 kW | 70 kW | 48 kWh + 38 US gallons |

The values shown in Table 7 are "generic" due to the dynamic behavior of the individual components. These include the IC engine, generator, batteries, motor, the motor inverter, and the auxiliary inverter. The performance of each is affected by electromagnetics, thermal issues, "source" impedance, and control software. The output of the entire system, therefore, becomes difficult to predict accurately. The output has not been modeled with the needed details to optimize operation in either battery-only mode or hybrid mode.

The information shown in Table 7 was also generated using the following information:

- Maximum continuous power for the batteries is based on a 1 hour discharge rate published by the battery manufacturer. Battery performance can change with SOC, temperature, discharge rate, etc.
- Useable energy for the battery-only drive mode is based on the quoted value from the battery manufacturer of one discharge of the battery system at a 2 hour rate from 100% to 10% SOC. Useable energy for the engine/generator-only drive mode is taken to be 95% of one full tank of gasoline. A 40 US gallon tank was installed on the vehicle.
- On its own, the engine/generator is capable of a maximum power of about 150 kW. Coupled with 96 kW from the batteries, the maximum power during hybrid drive (engine/generator + batteries) would be about 246 kW. During engine/generator-only drive or hybrid drive, however, the output power of the

drivetrain system is limited by the traction motor. Therefore, the values shown are those published by the traction motor manufacturer.

Using computer simulations, operation of the OCC 28 ft. multi-mode shuttle was examined for use on a CBD + Arterial cycle, as well as the Quebec City ÉcoloBus route. The simulations included the battery-only drive mode as well as various hybrid drive modes. Unless otherwise stated, the discussion and graphs are based on the vehicle loaded to its GVWR carrying 28 passengers (seated and standing passengers), with 8 kW required for auxiliaries, and drivetrain efficiencies taken into account.

A summary of the overall results of the computer simulations is shown in Table 8.

**Table 8**
**Overall Results of Computer Simulations for CBD Cycle and Quebec City Route for the OCC Bus***

| **Route** | **Criteria** | **Operating Mode (Calculated values shown in brackets)** | |
|---|---|---|---|
| | | **Battery-Only** | **Hybrid** |
| CBD | 0 - 32 km/h, 10 sec, 0% slope | NO (12 sec) | NO (12 sec) |
| CBD | 32 km/h continuous for 18.5 sec | YES | YES |
| Arterial | 0 - 64 km/h, 29 sec, 0% slope | YES (28 sec) | YES (25 sec) |
| Arterial | 64 km/h continuous for 22.5 sec | YES | YES |
| Quebec | 0 - 30 km/h, 20 sec, 7% slope | YES | YES |
| Quebec | Start from 0 km/h, 13% slope | NO (11%) | NO (11%) |

* Values calculated for maximum passenger loading and 1% grade unless otherwise specified
Refer also to Table 9 for parameters used in computer simulations

### 2.16.1 Central Business District + Arterial Cycle

The computer simulation of the CBD cycle requires accelerations from 0 to 32 km/h in 10 seconds (0% grade). The time required to accelerate over these speeds is approximately the same for the shuttle operating under any drive mode. The calculated time for the shuttle to accelerate to 32 km/h (1% grade, 28 passengers) was found to be approximately 12 seconds. This is just outside the 10 second requirement shown in Table 8.

The cycle requires the vehicle to travel at a constant speed of 32 km/h for periods of 18.5 seconds. With 28 passengers on board and 1% road grade, the power required to maintain a constant 32 km/h is approximately 20 kW. This is achievable for the shuttle operating under any drive mode.

The cycle also requires accelerations from 0 to 64 km/h in 29 seconds (0% grade). The power required to accelerate over these speeds is achievable for the shuttle operating under any drive mode. The calculated time for the shuttle to accelerate to 64 km/h (1% grade, 28 passengers) was found to be approximately 28 seconds for battery-only mode with 3 batteries. Acceleration time is expected to be slightly less in hybrid mode, at approximately 25 seconds.

The cycle requires the vehicle to travel at a constant speed of 64 km/h for periods of 22.5 seconds. With 28 passengers on board and 1% road grade, the power required to maintain a constant 64 km/h is approximately 50 kW. This is achievable for the shuttle operating under hybrid drive mode. In battery-only mode with three batteries, this requirement is at the limit of the battery system for continuous operation (i.e., at a 1 hour discharge rate) without auxiliaries. The short duration required, however, allows the speed to be maintained under higher discharge rates, but battery temperature may become an issue and system cooling could be required.

The graph in Figure 23 shows the effect of periodic interim charging from the grid to keep the OCC multi-mode prototype bus running in battery-only mode (i.e., grid-battery hybrid) for the normal working day for the CBD + Arterial cycle. Taking full advantage of the energy available from the three ZEBRA batteries placed on the bus, a dedicated grid-battery hybrid operation would require seven 20-minute fast charges throughout a 12 hour day, with 11 circuits being completed. With five on-board batteries, the vehicle would require six fast charges to complete 11 circuits; and seven on-board batteries would require five fast charges for 11 circuits. Optimized buses with five or seven on-board batteries would have the engine/generator removed, and therefore better range and kilowatt-hour per kilometre performance.

The graph in Figure 24 shows the effect of operating the IC engine at a specific power level (i.e., specific engine speed) to keep the OCC multi-mode demonstration bus running in hybrid mode (engine/generator + batteries) for a normal working day for the CBD + Arterial cycle. In this simulation, there are no short periods of engine idle time or engine start and stop cycles, and the power required from the engine/generator was calculated so that the battery energy is replaced over the course of one cycle.

It is unlikely that the “ideal” scenarios discussed above would be applied in real-world driving situations. The strategy for power sharing between the engine and batteries must include factors such as battery SOC, instantaneous power or torque demand (as dictated by driver style, passenger loading, road conditions, etc.), and other system limitations (such as battery temperature, etc.). Also, it may not be socially acceptable (to the driver, passengers, or pedestrians) to have the IC engine running at high power (to charge the batteries) while the vehicle is stationary. The models simply show various possibilities offered by the multi-mode drive.

A possible charge-maintaining strategy would be one in which the batteries provided the only power during initial periods of acceleration, during low vehicle speeds, and during idle periods (to power the auxiliaries). The IC engine could be run at all other times. In this case, battery energy would be continuously "topped up", and there would be many short periods of low engine speeds and engine start and stop cycles. In this scenario the batteries would not be deeply discharged.

It is very difficult to produce meaningful models for charge-maintaining strategies without accurate emissions models. These simulations serve mainly to "bound" the possible expectations for improvements in performance or emissions due to hybridization. It is assumed that weight savings and improved engine management or post-combustion improvements could be equally well applied to simple engine driven vehicles.

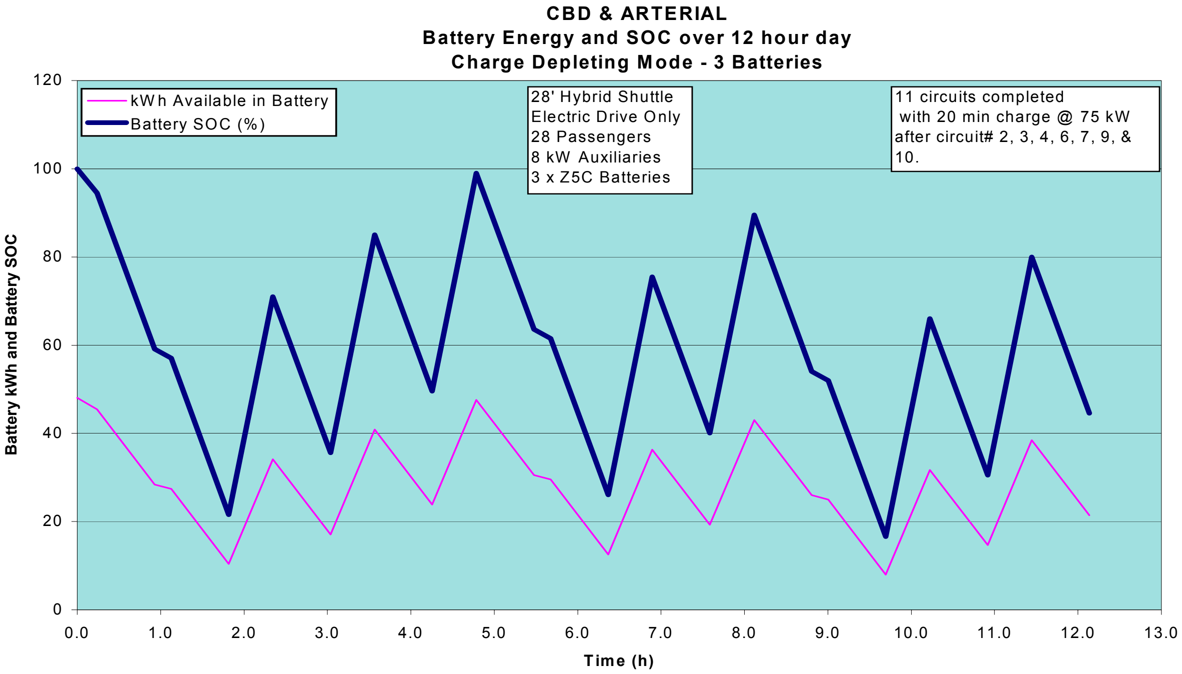


**Figure 23** Battery energy and SOC for operation of the prototype bus on the CBD cycle over 12 hours in battery-only mode

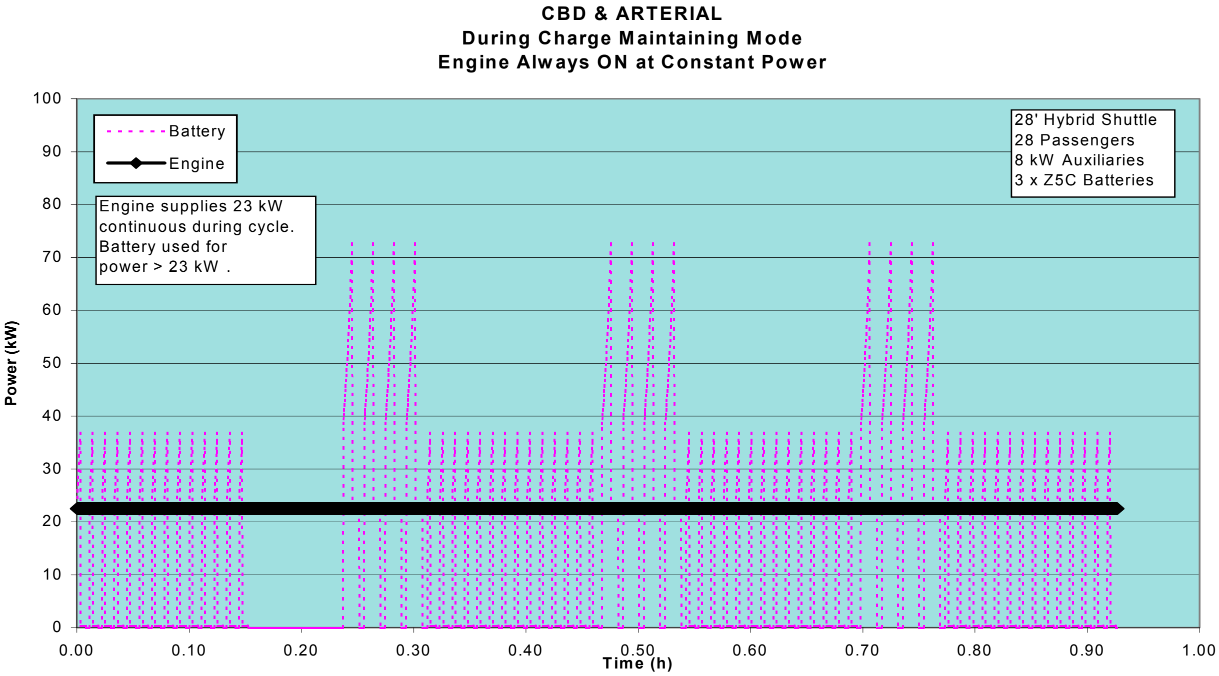


**Figure 24** Power profile for operation of the prototype bus on the CBD cycle over 12 hours in a charge-maintaining hybrid strategy

### 2.16.2 Quebec City ÉcoloBus Route

Segments of the Quebec City ÉcoloBus route require typical accelerations of about 0 to 30 km/h in 20 seconds (up to 6.6% grade). The total power required to perform such accelerations is roughly 50 to 70 kW. A worst-case acceleration of approximately 0 to 20 km/h in 15 seconds (7.5% grade) is also required. The total power required for these conditions is approximately 88 kW. These short-term powers and acceleration times are possible for the shuttle operating under any drive mode.

Typical speeds of 20 to 30 km/h for 15 seconds were registered. At a 1% road grade, the power required to maintain these speeds is roughly 20 to 45 kW. This is possible for the shuttle operating under any drive mode.

Peak speeds near 35 km/h (1 second) are required over several points in the route. The power required to maintain 35 km/h is roughly 35 kW at low road grades, which is possible for the shuttle operating under any drive mode. The data supplied for the route showed that this speed was never maintained for more than 1 second, so this should not be viewed as a continuous power requirement for the route.

A worst-case startability of 13% is needed for the Quebec City route. With the present gearing, this is just beyond the capabilities of the prototype shuttle when fully loaded (28 passengers), but would be possible when moderately loaded (15 passengers).

The graph in Figure 25 shows the effect of periodic interim charging from the grid to keep the OCC multi-mode prototype bus running in battery-only mode (i.e., grid-battery hybrid) for the normal working day for the Quebec City ÉcoloBus route. Taking full advantage of the energy available from the three ZEBRA batteries placed on the bus, a dedicated grid-battery hybrid operation would require four 20-minute fast charges throughout a 12-hour day with 19 circuits being completed. With five on-board batteries, the vehicle would require four fast charges to complete 20 circuits; and seven on-board batteries would require three fast charges for 20 circuits. Optimized buses with five or seven on-board batteries would have the engine/generator removed and therefore better range and kWh/km performance.

The graph in Figure 26 shows the effect of operating the IC engine at a specific power level (i.e., specific engine speed) to keep the OCC multi-mode demonstration bus running in hybrid mode (engine/generator + batteries) for a normal working day for the Quebec City ÉcoloBus route. In this computer simulation, there are no short periods of engine idle time or engine start and stop cycles, and the battery energy is replaced over the course of one cycle.

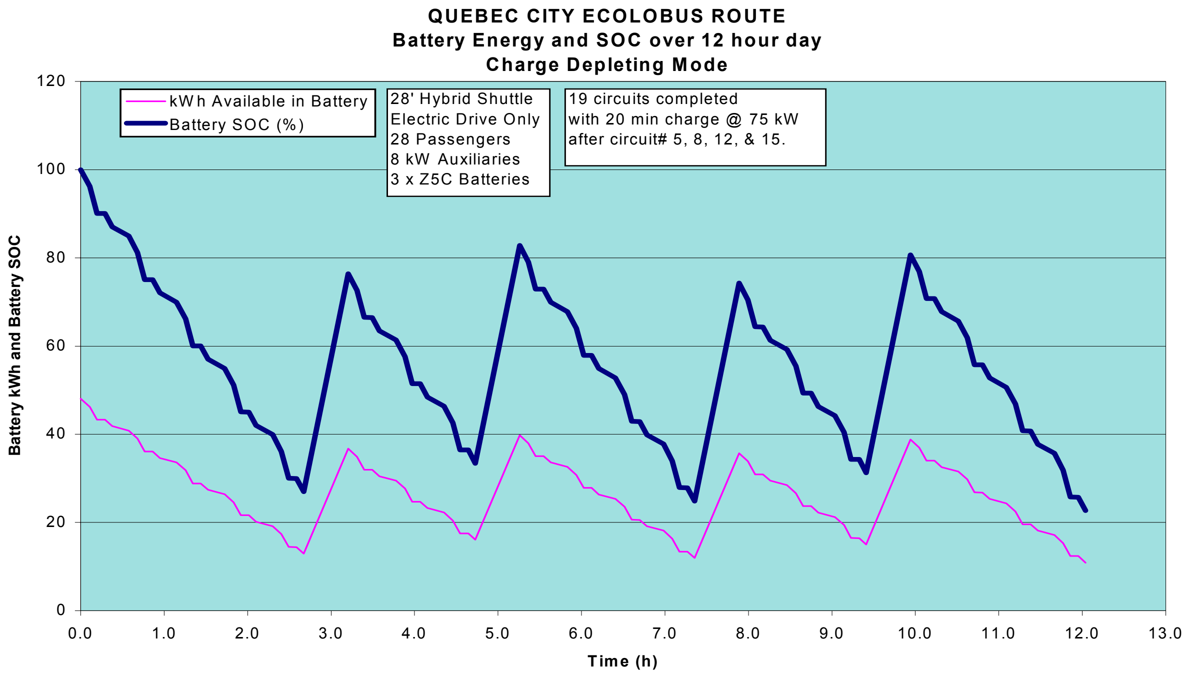


**Figure 25** Battery energy and SOC for operation of the prototype bus on the Quebec City route over 12 hours in battery-only mode

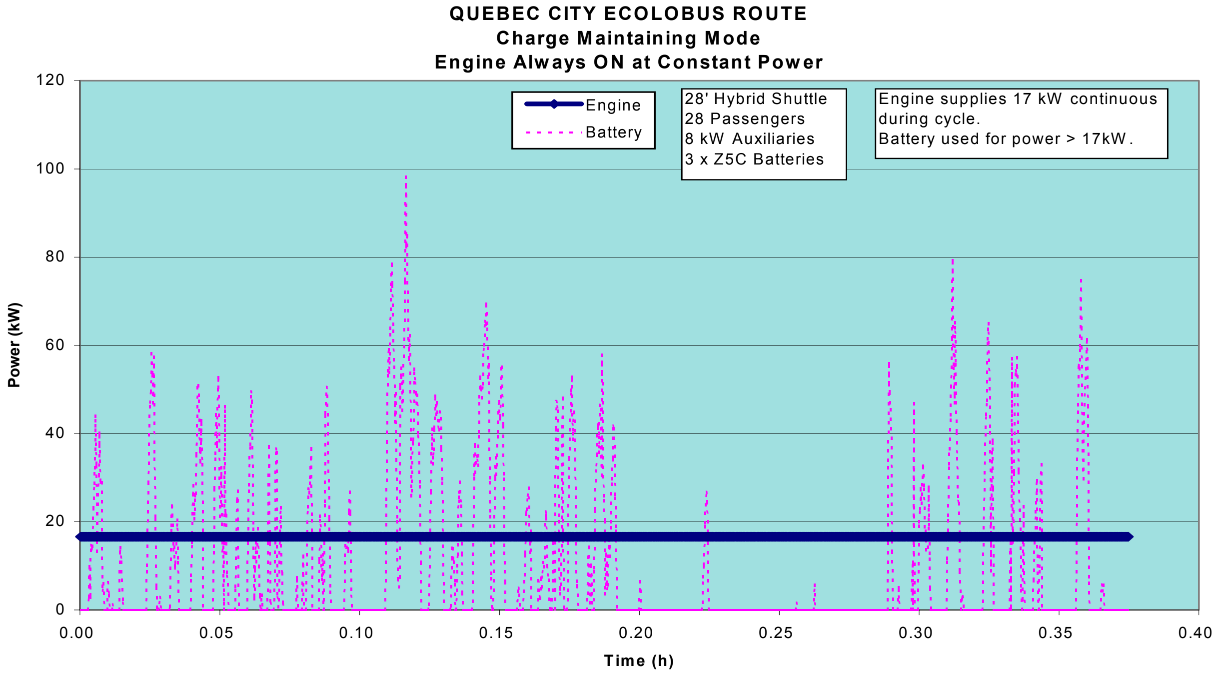


**Figure 26** Power profile for operation of the prototype bus on the Quebec City route over 12 hours in a charge-maintaining hybrid strategy

### 2.16.3 Energy Efficiency

The computer analysis of power and energy requirements over the various routes described in Section 2.16.1 and Section 2.16.2 was based on a single set of parameters and efficiency values for the traction motor, transmission, and all other components, as shown in Table 9.

**Table 9**
**Vehicle and Drivetrain Parameters for the Prototype Shuttle**

| Vehicle Type: ELF 28 ft. Multi-Mode Hybrid Electric Shuttle Bus | | |
|---|---|---|
| GVWR | kg | 8,617 |
| Coefficient of Rolling Resistance, Fr | | 0.015 |
| Aerodynamic Drag Coefficient, Cd | | 0.46 |
| Frontal Area Projection, A | $m^2$ | 6 |
| Tire Roll Radius (Loaded) | m | 0.389 |
| Maximum Motor Torque Available | Nm | 350 |
| Estimated Motor + Inverter Efficiency | % | 92 |
| Estimated Transmission Efficiency | % | 96 |
| Differential Gear Ratio | | 5.13 |
| Reducer Gear Ratio | | 2.6 |
| Final Drive Ratio | | 13.338 |

Efficiency information for the operation of the Siemens traction motor with its inverter, as well as operation of the Siemens generator with its inverter, was obtained directly from Siemens and is shown in Figure 27 and Figure 28 (the km/h values shown are specific to the OCC bus). The data is based on steady-state conditions with a supply voltage of 650 V DC. According to Siemens, the estimation for efficiency below 1,000 rpm would be to keep the losses constant. This same data was applied without any de-rating to the dynamic conditions of the CBD profile or the lower voltage supplied by the ZEBRA batteries (OCV = 557 V DC).

The efficiency of the Ford gasoline powered engine was not known, so this information has not been incorporated into the analysis. The analysis also did not account for the efficiency of the MES-DEA ZEBRA batteries since this information was also not known. For example, the batteries used in this project have an average internal resistance of approximately 1.8 Ohms. The efficiency changes with battery current and delivered power, and also with battery SOC. A total, constant output of 30 kW from the three batteries on the prototype bus at a moderate state of charge results in an equivalent resistive loss of about 0.66 kW/battery, or about 94% efficiency.

The overall drivetrain efficiency used in the graphs shown in Figure 23 to Figure 26 was a constant 88%, found by multiplying the estimated motor efficiency and transmission efficiency values shown in Table 9.

Speeds of 32 km/h (approximately 2,900 rpm for the OCC bus) and 64 km/h (approximately 5,800 rpm), and typical resistive torques of 40 to 60 Nm are encountered in the CBD profile. It can be seen from Figure 27 that a typical value of the motor and inverter efficiency at these conditions is approximately 90%. Using a constant motor + inverter efficiency of 90% and transmission efficiency still estimated at 96%, an overall system efficiency of 86% (constant) can be calculated, which is very close to the estimated efficiency of 88% used in the initial analysis.

Graphs very similar to those of Figure 23 and Figure 25 were also obtained when the calculations were performed with the motor + inverter efficiency changing with motor speed and torque, and using the efficiency values provided by Siemens (Figure 27). Overall, the curves based on the different constant efficiencies as well as the curves using varying efficiencies were all very similar. Therefore, a single, constant efficiency value of 86% was determined to give a reasonable prediction of the overall efficiency of the drivetrain system used in the prototype OCC multi-mode shuttle bus.

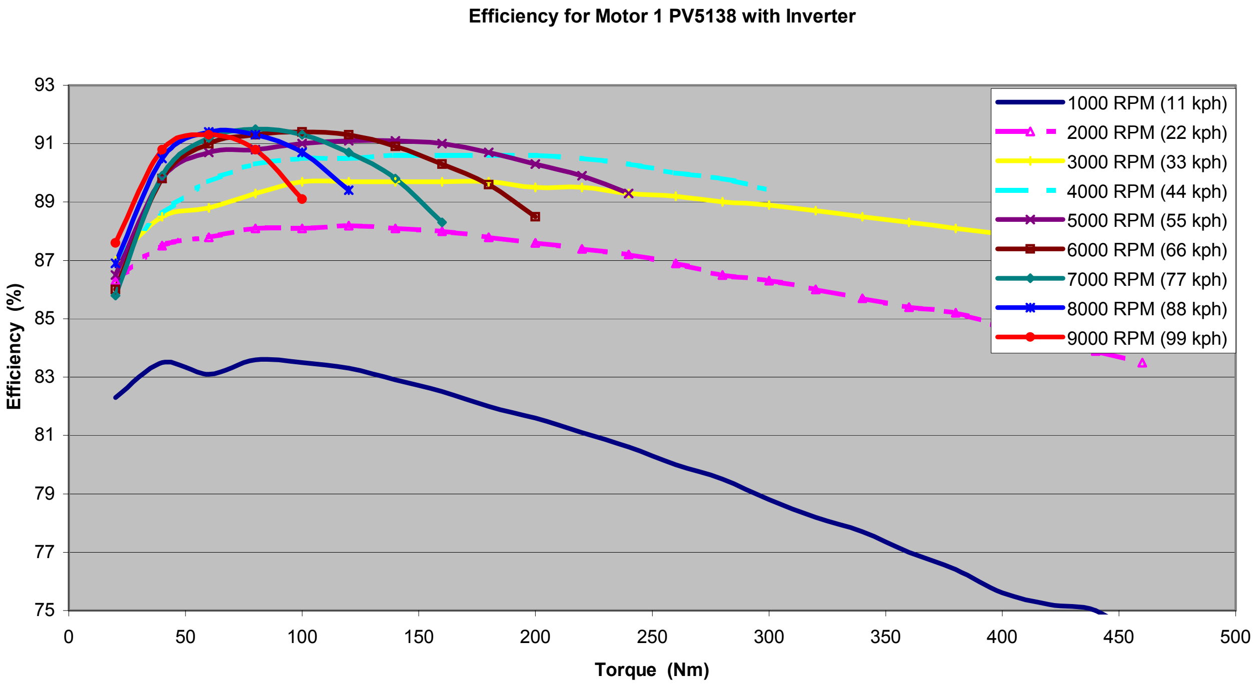


Figure 27 Efficiency of Siemens motor and inverter used on the OCC shuttle bus

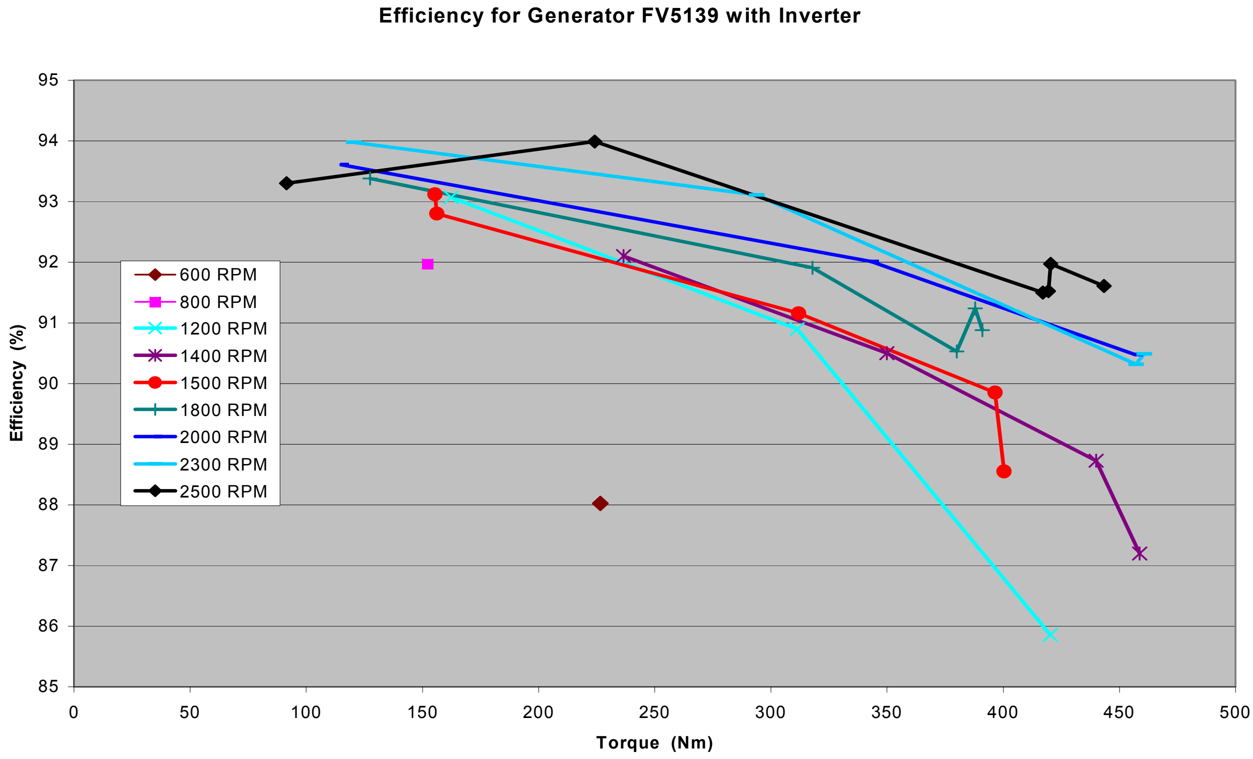


Figure 28 Efficiency of Siemens generator and inverter used on the OCC shuttle bus

## 2.17 Conclusions on Technical Feasibility

The boundaries for fitness for purpose for any electric or hybrid electric vehicle are defined by the choice of the powertrain in the given vehicle structure: *What on-road applications can be met making sensible use of the different hybrid drive options and charge strategies? What benefits and net reduction in emissions can be achieved from the different hybrid drive options?*

All major aspects of the prototype OCC multi-mode shuttle vehicle design, including engine and battery choice, drivetrain design, and control systems were based on demonstrating operational capability for different drive modes. Initial component and system choices were roughly based on meeting typical airport shuttle or CDB-type on-road applications, but flexibility was intentionally maintained to help ensure a that large range of different drive modes could be examined.

For strictly low-speed, slow acceleration duties, the low gear ratios and single motor drivetrain used in the shuttle design are acceptable. For strictly high-speed, fast acceleration duties, a higher gear ratio and possibly twin motors could be used. Where a vehicle is designed to meet a mixture of these duties, the vehicle may be over-designed or over-priced.

The number of batteries in the prototype vehicle was intentionally minimized to maintain acceptable costs. The flexibility of placing the batteries under the perimeter seating would allow up to seven batteries to be installed if required. With this much “battery” on board, the IC engine and generator would likely not be required, resulting in a true zero emission vehicle (grid-battery hybrid). Removal of the engine/generator powertrain would not result in major vehicle modifications. Conversely, the placement of the fuel tank under the rear seats allows for increased flexibility on the capacity of the tank. Additional range under engine drive modes could be achieved with a nominal increase in gas tank size.

The analysis of the previous sub-sections indicates that, with additional batteries, all-day operation in battery-only mode may be possible if fast charging is available. The weight reduction impact is approximately 687 kg (refer to Table 5) if the engine/generator and fuel tank were to be removed. This weight is approximately equal to three additional batteries, which if placed on board would nominally double the battery-only range of the prototype vehicle with its three batteries, but would still result in the need for fast charging throughout the day. Conversely, if the engine/generator and fuel tank were removed and not replaced with additional batteries, the vehicle curb weight would decrease by about 10%, resulting in a nominal 10% increase in battery-only range (based on an average kWh/kg/km basis), or a nominal 10% reduction in energy consumption for the same range.

There is no obvious optimum for the number of batteries to run all day in battery-only mode. Battery purchase costs must be taken into account, and the more battery, the lower capacity available for passengers; however, more battery means fewer fast charges are required as well as reduced power and current requirements from each individual battery, possibly resulting in longer battery life. Conductive charging, in which a direct connection is made between the bus and off-board supply is the most efficient form of charging, and a plug connection offers a visual and mechanical assurance that the proper connection has been made. Fast charging throughout the day, however, requires that an individual, likely the driver of the bus, first plug in and later unplug the vehicle, which may not be acceptable for transit operators. Other options include automated connections such as the use of roof-mounted pantographs, or inductive charging in which the bus may be parked over charging plates embedded in the road. In the prototype bus, the engine/generator allows for all-day driving without the need for fast charging, but does result in some emissions when the engine is operating.

Following validation of the actual components and sub-systems on a test rig at BET (refer to Section 4), the vehicle design was ultimately proven out with the development and on-road testing of a real, working vehicle. Initial designs and actual development of the hybrid powertrain proved that the drive components for the shuttle could be placed within the powertrain area of the base vehicle. Choices regarding the number of batteries, number and size of motors, gearing, etc. were made on this basis, and the vehicle was proven to meet the 28-passenger capability within the upgraded GVWR.

As outlined in Section 1.5.5, vehicle design requirements such as ergonomics, ease of repair, fueling ease and safety, crashworthiness, visibility, low floor construction and other paratransit requirements were all maintained at the same level as the base vehicle due to the limited design changes employed.

In addition to vehicle design constraints, vehicle performance guided component choice. Preliminary calculations for vehicle performance indicate that operation in the CDB + Arterial cycle was feasible, and operation over the Quebec City route would be at the limits of vehicle performance. These conclusions, especially for factors such as startability and gradeability, were based on a number of assumptions relating to control algorithm design and relationships between battery load voltage, generator output, and powertrain capabilities.

Design studies, computer simulations, and overall systems and performance testing indicated that this project is technically sound. In-service operation forms the next step required to prove out the vision of the project. Refinements will need to be made to the vehicle design and component choice where the following deficiencies were identified:

- The limited control flexibility for engine operation in hybrid mode
- The need to further optimize the energy and power management of the auxiliaries
- The need to implement further vehicle weight reduction and thermal management measures

Each of these issues could be resolved through further examination in a follow-up optimization project. A follow-up prototype vehicle based on such improvements would then be warranted.

# 3. COMMERCIAL FEASIBILITY

## 3.1 Capital and Operating Costs

Hybrid and pure electric powertrain technology is still in its early days so cost modeling at this stage is not accurate for the following reasons:

- Only prototype component and fabrication costs are known;
- There is little operating experience with the vehicle to accurately assess costs; and
- Hybrid operating strategies can be extremely varied and can significantly affect the emissions, the fuel consumption and possibly the battery life.

Discussions regarding costs are thus only indicators. Experience during this and future projects will help to firm up the estimates.

The costs and probable prices are most meaningfully expressed as incremental over a typical transit price for an OCC 28 ft. diesel shuttle. The incremental costs for additions and subtractions to the base vehicle to achieve a production-level vehicle equivalent to the hybridization of the prototype multi-mode vehicle would result in a premium likely in the area of about 80% to 100%. The initial terms of reference of the prototype OCC multi-mode shuttle project were to have the target price no higher than a 100% premium over a typical transit price. Although present capital costs for hybrid buses of various types are higher than for equivalent conventional buses, even a small cost premium is clearly not sustainable unless there is a dramatic change to the political attitude toward the costs of reductions of $CO_2$ and emissions. What is an acceptable premium will only become apparent with time.

The incremental costs incurred for the OCC/BET hybridization over the base OCC 28 ft. diesel shuttle are expected to decrease with higher volumes and with experience. Components that should have the largest drop in price include the traction and auxiliaries inverters, as well as specialty items such as the engine-to-generator adaptor and gear reduction box. The price of the batteries is also expected to fall with increased volume and improved design.

The higher purchase price of the OCC hybrid shuttle will also be offset by reductions in operating costs due to:

- reduced fuel consumption;
- reduced brake maintenance (due to regenerative braking);
- reduced engine and transmission maintenance; and
- longer engine life because high power and idling is avoided.

Typical transit buses have an average fuel consumption of about 6 mpg (imperial gallons). In the city and with stop-start CBD duty this falls to about 5 mpg. Based on an average 50,000 miles/year, at Cdn$3/gallon the fuel cost could be as high as Cdn$30,000/year. With the OCC/BET hybrid powertrain architecture, the "U-shaped" curve of specific fuel consumption of the engine can be fully exploited by keeping the engine operating in the optimum region (at the bottom of the "U"). Furthermore, in North America, fuel costs per mile can be more than six times that of electricity costs per mile from the grid. Therefore, a projected annual savings by changing to hybrid could be Cdn$15,000 to Cdn$20,000, depending on the hybrid strategy (i.e., charge-maintaining or charge-depleting). These estimates will be verified by experience.

One option that would help reduce the capital price of the bus would be to lease the batteries to the vehicle operator. The capital price would then be similar to a typical transit bus. The lease costs of the batteries could be accounted for through operating costs, which would be close to the diesel fuel costs savings.

It is not difficult to imagine a saving of Cdn$5,000/year on scheduled maintenance due to reduced brake service, no transmission service, less engine service, etc. Also, the engine and transmission in a typical diesel vehicle normally has a major overhaul/rebuild (Cdn$10,000) after 300,000 km. Within the four- or five-year expected lifetime of the battery set, this major overhaul should not be required for the hybrid shuttle. It will be deferred until much later since high engine demands as well as engine idle periods would be reduced.

For a 28 ft. shuttle designed as a pure electric vehicle, the engine/generator and associated hardware would not be required. The fuel tank would also be removed. For CBD-type duty, at least four ZEBRA batteries would be required, with six making more operational sense. The incremental costs for additions and subtractions to the base vehicle to achieve a production-level pure electric vehicle with six batteries would be only moderately more than that of a hybrid vehicle. Operating a pure electric vehicle saves all of the diesel fuel cost and adds back a relatively small electricity charge. Fuel savings up to Cdn$25,000 per year could be possible. The savings in maintenance costs would be slightly more than a hybrid vehicle since the engine overhaul would be eliminated, although much of the overall savings would be offset by the replacement costs for additional batteries.

Table 10 shows that a 28 ft. hybrid or pure electric shuttle with a 10 year life could result in a small but positive net savings over a similar diesel vehicle. The net financial savings is an inexact and possibly optimistic scenario since the results are very dependent on the additional capital cost and the fuel savings. If the price of fuel increases the savings should increase. The price of the batteries is the biggest item and there is a real prospect that the prices will reduce over time, possibly by a factor of 2. This will affect both the additional capital cost and the replacement cost and so the net savings should increase significantly. The same comments apply to the drivetrain components and electronics since prices are also volume dependent.

**Table 10**
**Preliminary Cost Feasibility Analysis for Electric and Hybrid Shuttle Compared to Standard Diesel Shuttle**

| | Hybrid Electric | Battery Electric |
|---|---|---|
| **CAPITAL COSTS** | | |
| Price of Conventional 28 ft. Diesel Shuttle: | $200,000 | $200,000 |
| Estimated Price of Hybrid or Electric 28 ft. Shuttle: | $360,000 | $410,000 |
| Difference: | $160,000 | $210,000 |
| Difference under Higher Volume Production: | $120,000 | $170,000 |
| **OPERATING COSTS** | Over 10 Years | Over 10 Years |
| Estimated Diesel Fuel Savings: | $150,000 | $250,000 |
| Estimated Maintenance Savings: | $ 50,000 | $ 80,000 |
| Estimated Cost of Battery Replacement (5 years): | $ 60,000 | $120,000 |
| Savings in Operating Costs (10 Years): | $140,000 | $210,000 |
| Estimated Net Savings over 10 Years: | $ 20,000 | $ 40,000 |

Operating costs are dependent on energy consumption (whether fuel or electricity), and this is directly related to vehicle weight. Future vehicles must seek to further reduce weight to improve operating economies.

The pressure to reduce weight and cost raises the issue of compromise in some areas. For example, many larger hybrid electric buses use dual traction motors to provide higher margins of performance, such as for startability and gradeability. However, this adds weight and cost. Compared to the prototype OCC bus, these vehicles would have an extra motor, an extra inverter, and a high-power mechanical combiner for the two motors.

The prototype OCC shuttle project chose to stay with one traction motor with the intent for follow-up developments to reduce the vehicle weight, thus reducing the compromise. Realistic penetration of markets with this type of vehicle will depend on issues such as costs, government and regulatory incentives and sanctions, and attitudes of fleet operators. The guiding principle is that the vehicle must be reasonably commercially competitive over its lifetime, otherwise operators will not use it, irrespective of emissions benefits.

### 3.2 Conclusions on Commercial Feasibility

The key to commercial feasibility lies in the practical viability and economics of the energy storage system, i.e., the ZEBRA battery. Other batteries such as NiCd could be considered, but due to their limitations (i.e., lower energy, difficulty for parallel connection, difficulty with high voltage, high cost, etc.) the scope of applications would be seriously limited. Currently, other advanced batteries such as lithium-based batteries come with too many complexities and unresolved issues for this application (e.g., high cost, high-voltage difficulty, safety issues, thermal problems, lack of technological maturity, etc.).

The figures would suggest that if there is a willingness to consider lifetime costs, the benefits of reduced emissions could come at no extra long-term cost even though the analysis presented in this document is both superficial and incomplete due to lack of detailed data.

The important conclusion, however, is that different hybrid modes can confer different benefits, and with flexibility of thought, the emissions benefits can be sensible economically. This could create a viable Canadian-based industry, albeit based on imported powertrain technology.

# 4. POWERTRAIN TEST RIG

## 4.1 Description

A test bench was assembled at BET Services that enabled part and full powertrain systems of the prototype shuttle to be tested prior to road testing.

The test bench operated with the bus partially assembled in which the engine/generator and auxiliaries were installed on the bus but the batteries, control electronics, and other components were placed on racking. During testing, the bus body was parked next to the test bench inside the facilities at BET, as shown in Figure 29.

A photo of some of the major test bench components is shown in Figure 30. The test bench comprised the following:

- Traction motor coupled to a motor shaft dynamometer to simulate driving loads up to 150 kW
- Two or three ZEBRA batteries
- Two duo inverters
    - One Siemens duo inverter controls the traction motor and generator
    - One duo inverter provides the auxiliaries feed and the on-board charger
- The 12 V battery charger (i.e., 110 V AC – 12 V DC inverter)
- The 110 V AC sine wave filters for the auxiliaries feed
- The 12 V – 24 V, 10 A DC-to-DC converter to provide 24 V DC for the Siemens units
- Water-cooling system for the dynamometer and the Siemens inverters, and the Siemens traction motor. The Siemens generator is cooled by the water cooler on board the vehicle.
- The signal links between the Siemens units and the ZEBRA batteries
- Power cables and other interconnections
- The 220 V, 3-phase, 70 kVA supply transformer, contactor and fuses to act as the off-board infrastructure for the on-board charger
- A 200 kW off-board high-voltage battery charger

Figure 29 Prototype shuttle bus on hoists beside the test bench at BET facilities

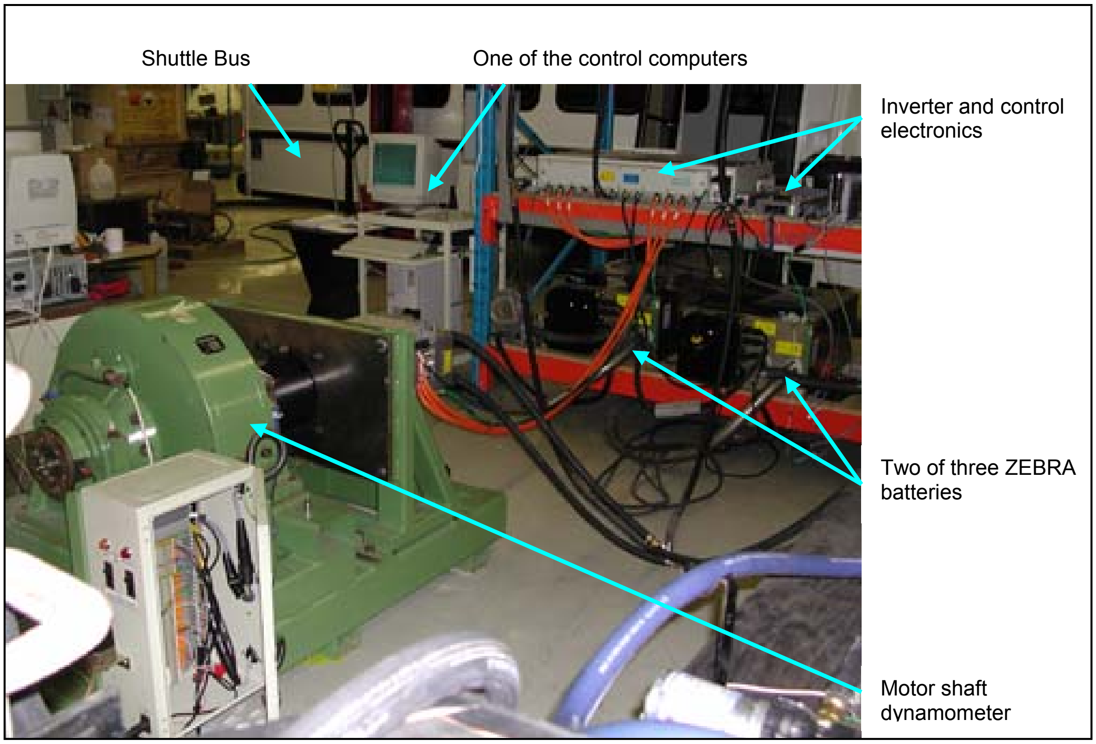


Figure 30 Photo of the test bench installed at BET Services

## 4.2 Bench Testing of the CBD Profile

The main purpose of the test rig was to prove out the various powertrain systems as well as various operating modes and hybrid strategies. The set-up could be used to simulate virtually any practical driving route and to explore different engine operating strategies (e.g., constant power output from a smaller engine, a turbine, or a fuel cell). For the purposes of the prototype OCC shuttle, the test rig was used mainly to investigate the 32 km/h acceleration portion of the CBD cycle.

The test rig was set up such that a speed request was sent to the traction motor through the Siemens DICO control system simultaneously with a resistive load signal (i.e., resistive torque) being sent to the dynamometer. The resulting motor speed, motor torque, and motor power were all recorded for analysis.

For testing of the CBD cycle, the Speed vs. Time of the CBD profile (Figure 8) was used as the motor speed request from the Siemens DICO control. The resistance of the vehicle's wheels against the road was calculated before the test using data based on the vehicle information (refer to Table 9) and the identical Speed vs. Time profile used for motor speed (Figure 8). The resulting calculation for resistive load was converted to values of resistive torque by multiplying the data by the vehicle tire roll radius and applicable gear ratios. This Resistive Torque vs. Time information was then used as the resistive load signal for the dynamometer.

The speed and power profiles for a 32 km/h excursion within the CBD cycle are shown in Figure 31 and Figure 32. This acceleration profile was run on the test rig under battery-only drive (charge-depleting, grid-battery hybrid). No auxiliary electrical loads were included in the dynamometer tests or the associated analysis.

Figure 31 shows that the actual motor speed matched the requested speed during the acceleration portion except at the initial and end-points of the acceleration where the requested (input) torque changed rapidly. Also, the actual motor speed closely matched the requested speed during the constant speed portion.

Figure 32 shows the resulting power information. In this graph, the motor power predicted from the computer model is based on the actual speeds measured for the motor, and not the ideal requested speed. As a reference, the predicted motor power is plotted in two forms:

1) When including all relevant resistive forces that the traction motor must overcome, the predicted power during acceleration matches well with the measured power, although the predicted curve peaks before dropping back down to match the measured value at constant speed.
2) The predicted power that is just required to overcome the various external resistances against the vehicle during the acceleration (i.e., rolling resistance, hills, aerodynamic drag) is also shown. This curve rises smoothly to eventually match the value at constant speed.

The second curve lies well below the first curve; the difference being the power required to accelerate the vehicle. The actual motor power displayed from the Siemens system lies very close to the first curve, while the predicted and measured power data matches almost perfectly during the constant speed portion of the profile.

For the graphs shown in Figure 31 and Figure 32, torque information was calculated in advance and inputted into the motor-shaft dynamometer to account for the forces associated with acceleration. Without these forces accounted for in the input data, the predicted total power required to accelerate the vehicle would not match the measured power.

The graphs in Figure 31 and Figure 32 were calculated based on a single, constant value of an overall system efficiency of 83%. With reference to the discussion in Section 2.16.3, this is slightly different from the estimated system efficiency of 86% based on a constant inverter + motor efficiency, or 88% based on the parameters shown in Table 9, but still validates the overall approach. A more precise analysis would have the system efficiency changing to match the changes in the motor + inverter efficiency with motor speed as shown in Figure 27. Motor efficiency drops off most dramatically at low speeds, however, and this is exactly where the motor and dynamometer differ from the input requirements. Therefore, a minimum of the first 10 seconds for the acceleration profile can be disregarded for this generic analysis, resulting in the acceptance of a constant value for the overall efficiency.

As described above, the results of some of the tests performed indicated that the test rig (dynamometer + traction motor) was not capable of reacting fast enough to match erratic changes in requested (input) torque. To examine this further, the 32 km/h excursion of the CBD profile was repeated, but with an artificially slow ramp in the resistive torque of the dynamometer during initial acceleration. The resulting measurements matched closely to the predictions as the acceleration rate was reduced, supporting the initial conclusion.

The power required to accelerate the motor against zero resistive load from the dynamometer was also examined to investigate the diverging results at the start of the acceleration. This experimental test was thought of as measuring the mass (inertia) of the motor/dynamometer system, or its efficiency. Although no resistive load was applied, the motor power rose and fell by approximately 5 to 8 kW when the requested speed increased, then returned to near zero when the speed was constant. Therefore, it may be assumed that perhaps 5 to 8 kW of power was required to overcome the mass and resistance of the motor/dynamometer system during acceleration, further contributing to the difference in the results of Figure 31 and Figure 32. This conclusion is also supported by the fact that the predicted and measured power data matches almost perfectly during constant speed, when acceleration forces are zero.

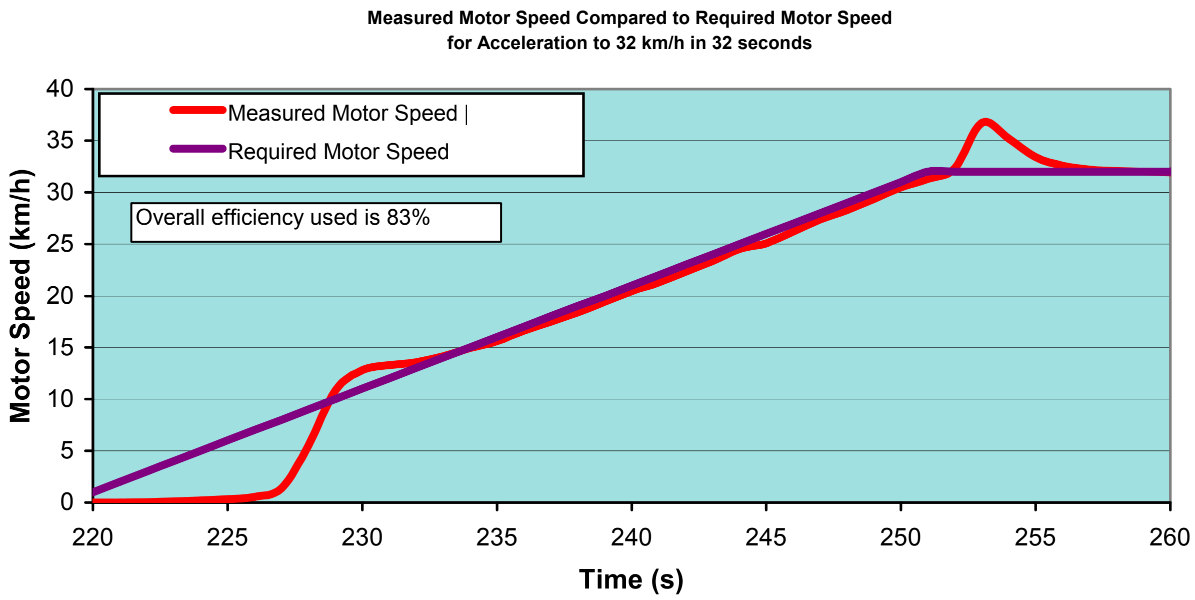


**Figure 31** Bench test results of motor speed during acceleration to 32 km/h

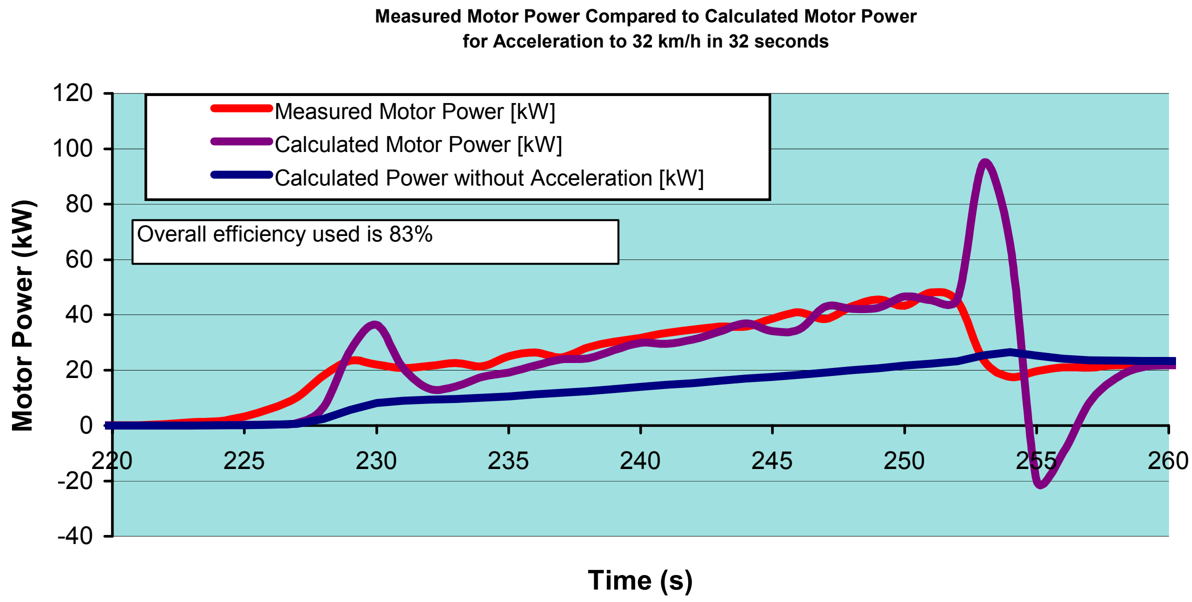


**Figure 32** Bench test results of motor power during acceleration to 32 km/h

## 5. HYBRID STRATEGIES

In traditional charge-maintaining hybrid systems, the strategy is mainly characterized by maintaining the battery SOC in a narrow band. Therefore, the battery is not required to be connected to the grid for battery recharge (essentially a “no-plug” system). All of the energy required to propel the vehicle, thermally manage the passenger area, etc. comes from the fuel, but emissions can be reduced by using the batteries to avoid operating the engine in regions of high emissions (e.g., engine idle and high power peaks) and to recapture regenerative braking energy.

In these systems, the amount of stored energy is normally quite small and the battery has a high power-to-energy ratio (typically >5 and ideally >10). This becomes increasingly more difficult with larger vehicles and the emphasis shifts to the need for a greater energy exchange only possible with higher stored energy.

The higher energy content of ZEBRA batteries makes them ideally suited for large vehicles. Larger vehicles need high-voltage systems with a high-voltage battery. The only practical high-voltage battery at present is the ZEBRA. Furthermore, the ZEBRA battery cannot be operated as a true no-plug system due to the need for overnight SOC balancing/calibration.

Therefore, vehicles equipped with high-energy ZEBRA batteries have the opportunity to operate with a traditional charge-depleting strategy. This type of strategy is normally applied solely to pure electric vehicles, which would operate as grid-battery hybrids (using overnight and opportunity fast charging from the grid), and is mainly characterized by operating the battery over a large SOC band, typically 80% to 20% SOC.

In the multi-mode hybrid shuttle bus, the combination of ZEBRA batteries and a smaller sized engine/generator system allows for an increased operating flexibility that combines the characteristics of the traditional charge-maintaining and charge-depleting strategies.

In the multi-mode bus, the batteries are sized to provide the power and energy required to propel the vehicle and thermally manage the passenger area. Battery SOC will start from 100% each day as a result of overnight connection to the grid for SOC calibration. The engine/generator can be used to supplement battery energy to recharge the battery, and can also supplement battery power to the auxiliaries or the traction motor. A charge-depleting strategy of this type may or may not take advantage of daytime charging from the grid. Also, the engine/generator can be significantly downsized from that of a typical transit vehicle. Most of the vehicle’s traction power would come from the batteries, with supplements from the engine/generator. When required to operate, the engine could be run under its optimum conditions, but could also be available to supply high power. Idling of the engine/generator would still be avoided.

The flexibility of the multi-mode operation of the hybrid shuttle bus using ZEBRA batteries raises the issue of intelligent control and allows hybrid strategies to address when the engine be might allowed to run and at what power. The proportionately higher amount of stored energy of the ZEBRA batteries allows such decisions to be made on the basis of the engineering strategy (e.g., SOC management, when power exceeds a set value, avoid engine idling, etc.), as well as a possible social strategy (e.g., if some emissions are inevitable, where should they be dumped?).

The control of the operating strategy and degree of power sharing between the batteries and engine/generator could thus be one or a combination of the following:

- pre-determined, if the route is well-known and predictable (e.g., similar to Quebec City);
- controlled by the driver to allow some flexibility;
- triggered from roadside beacons or on-board GPS, or other intelligent software controls to avoid problems created by route variations.

The options, given multi-mode capability, can be summarized as follows:

- “LAISSEZ-FAIRE”: Let emissions from charge-maintaining or charge-depleting systems fall when and where they will, dictated by the engineering strategy of the vehicle system.
- “NIMBY” (Not in My Back Yard): Decide where the emissions can be best tolerated and control the strategy of the charge-maintaining or charge-depleting strategies to achieve this objective.
- “ZERO LOCAL TOLERANCE”: Decide that emissions are not tolerable anywhere locally and use only grid-battery hybrids or battery-only drive mode (emissions will then all be at the power plant). This could be good news in provinces such as Quebec and British Columbia, with their water-generated hydro, but would remain an emissions issue in Southern Ontario or Alberta with continued use of coal-fired stations.

The graphs in Section 2.16 show the result of modeling for the Quebec City ÉcoloBus route and the CBD – Arterial cycle (typical of an airport shuttle application).

These models can form the basis for debate on appropriate intelligent control strategies. For example, it is very tempting with the Quebec City route to suggest that the engine should only run while the bus is climbing the steep hill and that the battery SOC should be planned to return to the set value at the end of each circuit (i.e., at the waterfront). However, if the steep hill area tends to trap emissions and noise (e.g., due to high buildings, etc.), then it might be better to run the engine to recharge the batteries along the waterfront where the wind could disperse the emissions more quickly.

The multi-mode strategy was able to be achieved in the prototype OCC multi-mode shuttle bus because of the use of the high-energy ZEBRA batteries. The strategy would not have been able to be implemented, however, without the Siemens control electronics system. The Siemens DICO controller used in the bus was capable of controlling the vehicle in all of its different operating modes (battery-only mode, hybrid mode, and diesel electric mode in which only the engine/generator operated without any power from the traction batteries).

The ability to implement the different social and environmental management strategies described above, however, is currently outside of the limitations of the basic Siemens system, so these concepts were not implemented in the prototype OCC multi-mode shuttle bus project. Also, finer optimization and implementation of more hybrid strategy options would require a much more detailed examination of the powertrain system efficiencies and life-cycle performance than that undertaken in the OCC bus project. This would include a careful analysis of items such as the engine’s brake specific fuel consumption curve, as well as the operating characteristics of the batteries.

There may not be a universally correct strategy, but what is more likely to be important is the ability to apply intelligent control and, ultimately, to enable the fuel consumption and emissions to be optimized for a particular duty cycle or application. This is probably the area where multi-mode strategies make most sense.

## 6. IC ENGINE CONTROL

During integration of the prototype vehicle, one of the main issues encountered was the limited control achieved for the speed of the IC engine.

As shown in Figure 18, the engine speed was controlled by a mechanical actuator connected to the throttle body. Rather than the throttle being directly coupled to the accelerator pedal as in a normal IC vehicle, this was achieved electronically in the OCC shuttle. The Siemens DICO would receive electronic signals based on the accelerator pedal position, and then send signals to the actuator to pull on the throttle, thereby increasing engine power. The signals to the actuator depended on the drive mode and hybrid power-sharing strategy implemented between the engine/generator and batteries so that the speed and power required from the engine could be completely independent of the speed and power requirements at the wheels.

It was found that the response of the engine speed to input signals to the actuator could be controlled only to a limited extent. The engine could not be made to respond in a fast and perfectly smooth manner as in any ICE vehicle. The reasons for the limitation were the actuator hardware chosen and feedback loop used to control the engine speed. As a result, the Diesel Electric mode of operation, in which the vehicle is powered only by the engine/generator without any power from the traction batteries, was not implemented on the prototype shuttle. This also meant that, during hybrid mode operation, the engine was generally operated at discrete power levels rather than through a continuous spectrum, and was typically limited to no more than 50 kW (refer to Table 15). Finally, automatic start and stop of the engine/generator during vehicle operation was not implemented, so that during periods in hybrid driving when power from the engine/generator was not required, the engine was never turned off but instead was left to continuously idle.

Future vehicles would be better served through the use of a different type of engine, especially one based on CAN (Control Area Network) communication, rather than the analogue signal system implemented on the prototype shuttle.

## 7. VEHICLE SYSTEMS VERIFICATION

Once the vehicle integration was completed, operation of the vehicle was validated within the facilities at BET Services with the front drive wheels of the vehicle raised on an axle stand. After this testing, the vehicle was driven for short periods by BET personnel on public roads for initial shakedown tests.

A DVP&R (Design Verification Plan and Report) procedure was used to document each phase of the testing.

Such tests included validation of the braking system (with and without regenerative braking), acceleration, gradeability, startability, maximum speeds, forward and reverse operation, and overall energy consumption analysis.

Some of the issues addressed during this time included the following:

- Forward creep of the vehicle was adjusted so that the time required to build up from zero to the maximum creep torque helped minimize roll-back of the vehicle on hills.
- Operation of the OEM Drive/Neutral/Reverse selector was augmented with a dashboard-mounted push-button interface to improve the quality of engagement into the required selection. Start-up sequence lamps were also added as a visual aid to the driver.
- Brake pedal adjustments were made to optimize the point of regenerative brake and mechanical brake operation.
- Standard wiring to some components was replaced with shielded wiring to help minimize electromagnetic interference.
- The vehicle’s front drive axle, mechanical drive components and bushings were adjusted to help control the suspension under initial acceleration.
- Vibration from some components that might otherwise not be noticeable in a conventional diesel-powered vehicle required sound deadening.

Ultimately, the vehicle was proven operational, allowing more realistic and longer-term on-road testing to proceed.

# 8. ON-ROAD TESTING BY OCC

Following the bench test investigations and verification of the vehicle systems, the completed vehicle was demonstrated on local roads in multi-mode operation. This included driving the vehicle in battery-only mode and various hybrid mode strategies at various loaded weights.

Prior to on-road testing, the weight of the vehicle was measured using certified weigh-scales (results are shown in Table 11). The measurements revealed that the curb weight of the vehicle was 6,700 kg (14,765 lb.), which was approximately 300 kg (660 lb.) greater than the projected value of 6,418 kg (refer to Table 5). This was due to additional hardware such as air compressors, extra heaters, and filters for the auxiliaries inverter, which were added after the initial vehicle integration.

Most on-road testing was performed with a single driver and payload of salt bags totaling 1,245 kg (2,745 lb.), or at about 92% of the GVWR (i.e., total vehicle test weight of 7,945 kg).

**Table 11**
**Weight of Prototype Multi-Mode Shuttle During On-Road Testing**

| **Curb Weight*:** | (kg) | (lb.) |
|---|---|---|
| Front: | 2,385 | 5,255 |
| Rear: | 4,315 | 9,510 |
| TOTAL: | 6,700 | 14,765 |
| % of GVWR (8,617 kg / 19,000 lb.): | 78% | 78% |
| Maximum available payload: | 1,917 | 4,235 |
| Equivalent maximum # passengers: | 28 | 28 |
| **Total Weight During Testing**:** | (kg) | (lb.) |
| Front: | 2,415 | 5,320 |
| Rear: | 5,530 | 12,190 |
| TOTAL: | 7,945 | 17,510 |
| % of GVWR (8,617 kg / 19,000 lb.): | 92% | 92% |
| Payload weight during testing: | 1,245 | 2,745 |
| % of maximum available payload: | 65% | 65% |
| Equivalent # passengers: | 18 | 18 |
| * Full fuel tank (approx. 152 litres or 40 U.S. gal; approx. 103 kg or 225 lb.)<br>** Full fuel tank plus one driver plus salt bags | | |

A comparison of the overall results of the vehicle's performance during on-road testing by OCC with the design targets (Table 1) and calculations (Table 4) is shown in Table 12. The results indicate that the vehicle performed as expected on most requirements and was able to operate in typical shuttle or paratransit duty.

## Table 12
## On-Road Results vs. Calculations vs. Performance Targets for the Multi-Mode Prototype Vehicle

| Performance Items | Targets* (refer to Table 1) | From Calculations (refer to Table 4) | From On-Road Testing by OCC (Measured values shown in brackets) |
|---|---|---|---|
| Top Cruise Speed | ≥ 70 km/h / 43 mph | YES | YES (80 km/h / 50 mph) |
| Maximum Speed | ≥ 80 km/h / 50 mph | YES | YES (88 km/h / 55 mph) |
| Acceleration to 32 km/h | ≤ 10 sec | 12 sec | 18 sec to 48 km/h (30 mph) |
| Range: Battery-only | ≥ 60 km | YES | YES (70 km to 0% SOC) |
| Range: Hybrid | ≥ 250 km | YES | YES (≥ 500 km / 300 mi.) |
| Startability at 0 km/h | ≥ 20% grade | Starts up to 11% | Tested only to 7.3% |
| Gradeability at 35 km/h | ≥ 13% grade | Hybrid mode only | > 35 km/h at 7.3% |

* Values given for maximum passenger loading and 1% grade unless otherwise specified

The results of on-road range testing are presented in Table 13 and Table 14. In battery-only mode with two people on board and no other payload, the vehicle traveled a total of 58 km with the batteries discharging from 100% to 20% SOC. With a payload totaling 1,245 kg (2,745 lb.), the vehicle traveled a total of 53.5 km from 100% to 20% SOC. This equates to an average energy usage of 0.73 to 0.78 kWh/km, or about 0.103 kWh/tonne/km, which would result in a distance of about 70 km if 100% of the nominal battery energy were used. This is very close to the expected value for the driving conditions encountered. For example, the same prototype vehicle developed as a pure electric vehicle with five ZEBRA batteries instead of three would have a range of about 110 km using 100% of battery energy. This meets the performance target for the multi-mode prototype operated a pure electric vehicle, as shown in Table 1.

In hybrid mode, with a payload totaling 1,245 kg (2,745 lb.) and under demanding conditions, the vehicle traveled a total of 102.4 km with the battery SOC beginning at 80% and ending at 59.3% (net consumption of about 10 kWh), plus a fuel consumption of 28.2 L. The hybrid strategy used is shown in Table 15. This equates to an average fuel usage of approximately 27.6 L/100 km, or about 10.1 mi./U.S. gal. Using this average fuel consumption value, and with 150 L available on board, the prototype bus would have a range in hybrid mode well in excess of 500 km (300 mi.). This meets the performance target shown in Table 12.

The results of maximum acceleration testing on flat roads are presented in Table 16 and Table 17. As expected, the maximum acceleration times were fairly close for both battery-only mode and hybrid mode since the torque from the motor at low speeds is the same. Also, acceleration times did not vary significantly with SOC of the batteries. With a payload totaling 1,245 kg (2,745 lb.), the vehicle performed typical accelerations of 0 to 48 km/h (0 to 30 mph) in about 17.7 seconds. The vehicle accelerated over the ¼ mile (0.4 km) distance to about 66 km/h (41 mph) in about 34 seconds, which differs slightly from the calculated figure of 28 seconds (refer to Table 8).

The vehicle was tested for maximum acceleration while on a hill measured to have a grade of approximately 7.3%. The results are shown in Table 18. The test results are shown only for the vehicle running in hybrid mode. Although startability and gradeability were not measured for steeper hills, the vehicle was able to demonstrate that it could reach the 35 km/h target shown in Table 12 at a grade of 7.3%.

## Table 13
## Measured Range During On-Road Testing in Battery-Only Mode

| Weights | | Battery SOC (%) | Distance (km) | Motor System Temperature (°C) | Battery Energy Consumption |
|---|---|---|---|---|---|
| Payload (kg / lb.) | Test Weight (kg / lb.) | | | | |
| 136 / 300 | 6,836 / 15,065 | Start: 99.6<br>End: 20.0 | 58 | Start: 24<br>End: 40 | kWh/km = 0.73<br>kWh/tonne/km = 0.107 |
| 1,245 / 2,745 | 7,945 / 17,510 | Start: 99.0<br>End: 20.0 | 54 | Start: 20<br>End: 40 | kWh/km = 0.78<br>kWh/tonne/km = 0.098 |
| Tests carried out at relatively steady speed of 70 km/h (43 mph).<br>Average motor speed = 6220 rpm. | | | | | |

## Table 14
## Measured Range During On-Road Testing in Hybrid Mode

| Weights | | Battery SOC (%) | Fuel Used (L/US gal.) | Distance (km) | Battery Energy Consumption |
|---|---|---|---|---|---|
| Payload (kg / lb.) | Test Weight (kg / lb.) | | | | |
| 1,245 / 2,745 | 7,945 / 17,510 | Start: 78.2<br>End: 59.3 | 28.2 / 7.4 | 102.4 | kWh/km = 0.099<br>kWh/tonne/km = 0.012 |
| Test carried out in stop-and-go downtown driving and some arterial driving in hilly areas to a maximum speed of approximately 70 km/h (43 mph). All three air conditioners were ON during all driving (total of approx. 15 kW). Payload equates to about 18 passengers. | | | | | |

## Table 15
## Hybrid Strategy Implemented During On-Road Testing

| If the Battery SOC is*… | ..then the Power from the Engine/Generator will be**… | OR | If the Power Required at the Traction Motor is… | ..then the Power from the Engine/Generator will be**… |
|---|---|---|---|---|
| Below 50% | 30.0 kW (2300 rpm) | | 0 kW | 0 kW (idle, 760 rpm) |
| 50% - 60% | 22.5 kW (2113 rpm) | | 0 kW – 20 kW | 0 kW (idle, 760 rpm) |
| 60% - 70% | 17.5 kW (1988 rpm) | | 20 kW – 30 kW | 10 kW (1800 rpm) |
| 70% - 80% | 7.5 kW (1725 rpm) | | 30 kW – 40 kW | 30 kW (2300 rpm) |
| Above 80% | 0 kW (Idle, 760 rpm) | | 40 kW – 120 kW | 50 kW (2400 rpm) |
| * Left-hand columns in this matrix are designed to help recharge the batteries as the SOC drops, independent of the demand for traction.<br>**The engine/generator always delivers the higher power required between the SOC signal and the traction motor signal. | | | | |

## Table 16
## Maximum Acceleration During On-Road Testing in Battery-Only Mode

| Trial # | SOC | Time to reach ¼ Mile (0.4 km) (sec) | Speed at ¼ Mile (0.4 km) (km/h / mph) | Average Acceleration (G) | Time for 0 to 30 mph (0 to 48 km/h) (sec) | Peak Acceleration (G) |
|---|---|---|---|---|---|---|
| 1 | 90% | 34 | 65.3 / 40.6 | 0.054 | 18.2 | 0.123 |
| 2 | 80% | 35 | 62.4 / 38.8 | 0.050 | 19.2 | 0.115 |
| 3 | 70% | 33 | 68.4 / 42.5 | 0.059 | 15.9 | 0.128 |
| 4 | 60% | 33 | 68.1 / 42.3 | 0.058 | 16.2 | 0.141 |
| 5 | 50% | 31 | 75.6 / 47.0 | 0.069 | 13.9 | 0.131 |
| 6 | 40% | 35 | 63.9 / 39.7 | 0.052 | 18.6 | 0.118 |
| 7 | 30% | 35 | 63.4 / 39.4 | 0.051 | 19.0 | 0.166 |
| 8 | 20% | 36 | 59.1 / 36.7 | 0.047 | 20.5 | 0.128 |
| **Average** | | **33.9** | **65.8 / 40.9** | **0.055 G<br>=1.94 km/h/s** | **17.7** | **0.131 G<br>=4.63 km/h/s** |
| Test Conditions: Payload = 1,245 kg (2,745 lb.); Test Weight = 7,945 kg (17,510 lb.); No auxiliary load. | | | | | | |

## Table 17
## Maximum Acceleration During On-Road Testing in Hybrid Mode

| Trial | Time to reach ¼ Mile (0.4 km) (sec) | Speed at ¼ Mile (0.4 km) (km/h / mph) | Average Acceleration (G) | Time for 0 to 30 mph (0 to 48 km/h) (sec) | Peak Acceleration (G) |
|---|---|---|---|---|---|
| Trial 1 | 34.0 | 65.6 / 40.7 | 0.055 | 17.5 | 0.125 |
| Trial 2 | 34.2 | 64.8 / 40.2 | 0.054 | 17.7 | 0.120 |
| **Average** | **34.1** | **65.3 / 40.5** | **0.055 G<br>=1.94 km/h/s** | **17.6** | **0.122 G<br>=4.31 km/h/s** |
| Test Conditions: Payload = 1,245 kg (2,745 lb.); Test Weight = 7,945 kg (17,510 lb.). SOC = 46%. No auxiliary load. | | | | | |

## Table 18
## Startability and Gradeability in Hybrid Mode on Hill with Grade of 7.3%

| Trial | Time to reach ¼ Mile (0.4 km) (sec) | Speed at ¼ Mile (0.4 km) (km/h / mph) | Average Acceleration (G) | Time for 0 to 30 mph (0 to 48 km/h) (sec) | Peak Acceleration (G) |
|---|---|---|---|---|---|
| Trial 1 | 40.1 | 60.9 / 37.8 | 0.042 | 26.6 | 0.087 |
| Trial 2 | 44.4 | 51.9 / 32.2 | 0.033 | 35.9 | 0.082 |
| **Average** | **42.3** | **56.1 / 34.8** | **0.038 G<br>=1.34 km/h/s** | **31.2** | **0.084 G<br>=2.98 km/h/s** |
| Test Conditions: Payload = 1,245 kg (2,745 lb.); Test Weight = 7,945 kg (17,510 lb.) SOC = 65%. No auxiliary load. | | | | | |

## 8.1 Performance Testing

Following the on-road testing on local roads to demonstrate multi-mode operation, the vehicle was performance tested by an external third party. Testing was carried out by PMG Technologies at Transport Canada's Motor Vehicle Test and Research Centre in Blainville, Quebec.

The results of the performance testing are presented in Table 19, Table 20, and Table 21. In battery-only mode (three battery packs) and at ½ payload (919 kg of payload, equivalent to about 14 people on board, 7,678 kg total vehicle weight), the vehicle traveled a total of 106 km from 100% to 0% SOC. This equates to an average energy usage of approximately 0.50 kWh/km, or about 0.066 kWh/tonne/km based on the total rated energy of the battery network of 53.4 kWh. This was approximately 40% to 50% better than the values obtained during the on-road testing. This was expected since the range testing was performed in idealized conditions, but it does give an indication of the boundaries of maximum performance of the prototype vehicle.

The measured range was close to expectations from initial calculations when the conditions of the test were taken into account. For example, Table 2 shows that the power necessary to maintain a steady speed of 50 km/h on 0% grade for a fully laden vehicle is 21.4 kW. At the given test weight, the required power is calculated to be approximately 20.2 kW. Over 2.12 hours, this gives an ideal energy consumption of about 42.8 kWh with zero auxiliary power drain. This gives an overall efficiency of approximately 80% based on the rated energy of the battery network (53.4 kWh), which compares acceptably with the previous estimations (refer to Section 2.16.3). Note that the amount of energy as measured at the hydro meter to recharge the batteries from the range test was 60.4 kWh. Compared to the rated battery energy (53.4 kWh), this gives a charging efficiency of about 88%. Range testing was not performed in any hybrid drive modes.

The maximum acceleration times did not vary significantly between battery-only mode and hybrid mode. At ½ payload (919 kg payload), the vehicle accelerated to 50 km/h in about 18.3 seconds, which was very similar to the times obtained during the on-road testing (17.7 seconds to 48 km/h at 1,245 kg payload). As with the on-road testing, acceleration times did not vary significantly with SOC of the batteries. Acceleration times were significantly slower than initially targeted. The difference was a result of electronically limiting the maximum power to the Siemens traction motor to 80 kW, regardless of the operating mode. This was done to prevent abuse of the battery system, which had a maximum output in the region of 90 kW. With this limitation taken into account, the measured acceleration times matched the predictions fairly closely.

Top speeds were consistently measured to be about 83 km/h. This is similar to the top speeds obtained during on-road testing, and was exactly as expected since the speed of the motor was electronically limited to near this value to prevent over-speed of the Siemens motor.

Gradeability values (i.e., sustained speeds on a grade) were calculated from the acceleration test data obtained during the performance testing. Maximum values were calculated to be in the region of 13% at 5 km/h, and 7% at 35 km/h. The grade at 35 km/h was very close to that encountered during on-road driving as well as the maximum 8% grades expected for continuous battery-only drive based on initial predictions (as in Table 2).

Startability values (i.e., maximum grade that the vehicle can begin to move from rest) were not directly investigated during the performance testing. Instead, curb climb tests were simulated in which a wood panel of given thickness was placed immediately in front of the rear tires. The vehicle was able to mount a panel of ¾ in. (19 mm) thickness, but was not able to mount a panel of 1 in. (25.4 mm) thickness. Vehicles of this duty should be expected to overcome such an obstacle. Since the prototype vehicle was front-wheel drive, these tests had been performed with the trailing wheels blocked. Therefore, the curb climbing ability was greatly reduced. Similar curb climb tests were repeated during on-road testing at BET, but were performed instead in the standard test manner with the front drive-wheels blocked. For these tests, the vehicle was able to climb a 2½ in. (63.5 mm) panel, which more closely matched general expectations. Obviously, these test results are more a function of front-to-back weight distribution.

Other tests undertaken during the performance testing included noise measurements as well as dry and wet pavement brake testing (with regenerative braking disabled). Noise values were found to be above acceptable limits inside the vehicle in the vicinity of the bulkhead behind the driver's seat, which houses the two duo inverters and filters. This was as expected, and can be addressed in future vehicle designs. Brake testing confirmed that the systems installed by OCC were acceptable.

**Table 19**
**Measured Range During Third Party Performance Testing**
**in Battery-Only Mode at Half Payload**

| **Weights** | | **Battery SOC (%)** | **Distance (km)** | **Electrical Energy Measured at Hydro Meter** | **Battery Energy Consumption** |
|---|---|---|---|---|---|
| **Payload (kg / lb.)** | **Test Weight (kg / lb.)** | | | | |
| 919 / 2,025 | 7,678 / 16,922 | Start: 100<br>End: < 1 | 106 | 60.4 kWh | kWh/km = 0.57<br>kWh/tonne/km = 0.074 |
| Tests carried out at steady speed of 50 km/h (32 mph) on a dry, flat, circular asphalt test track with no auxiliaries. Results shown are the average over two tests. | | | | | |

**Table 20**
**Overall Results of Third Party Performance Testing**

| | | Acceleration 0 – 50 km/h (sec) | Acceleration 0 – 80 km/h (sec) | Top Speed (km/h) | Grade Limit (%) |
|---|---|---|---|---|---|
| **Half Payload** | **Battery-Only Mode** | 18.3 | 73.4 | 83.0 | 13.3 |
| | **Hybrid Mode** | 18.3 | 66.9 | 85.7 | 13.8 |
| **Full Payload** | **Battery-Only Mode** | 19.8 | 79.0 | 82.8 | 12.7 |
| | **Hybrid Mode** | 19.8 | 69.9 | 84.5 | 13.1 |

At Half Payload: Payload = 919 kg (2,025 lb.); Total vehicle weight = 7,678 kg (16,922 lb.).
At Full Payload: Payload = 1,851 kg (4,080 lb.); Total vehicle weight = 8,610 kg (18,977 lb.).
Grade Limit values are calculated. Results are the average over four runs at each condition.
Hybrid Mode conditions as in Table 15.

**Table 21**
**Performance Targets vs. Calculations, On-Road Results, and Performance Test Results for the Multi-Mode Prototype Vehicle**

| Performance Items | Targets* (refer to Table 1) | From Calculations (refer to Table 4) | From On-Road Testing (refer to Table 12) | From Performance Testing** (Measured values shown in brackets) |
|---|---|---|---|---|
| Maximum Speed | ≥ 80 km/h | YES | YES (88 km/h) | YES (83 km/h) |
| Acceleration to 32 km/h | ≤ 10 sec | 12 sec | 18 sec to 48 km/h | 20 sec to 50 km/h |
| Range: Battery-only | ≥ 60 km | YES | YES (70 km) | YES (106 km) |
| Range: Hybrid | ≥ 250 km | YES | YES (≥ 500 km) | Not Measured |
| Startability at 0 km/h | ≥ 20% grade | NO (11%) | Tested to 7.3% | 19 mm curb |
| Gradeability at 35 km/h | ≥ 13% grade | In hybrid mode | ≥35 km/h at 7.3% | 7% at 35 km/h |

*Targets given for maximum passenger loading and 1% grade unless otherwise specified.
**Performance testing results shown for battery-only mode.

## 8.2 Environment Canada Testing

Following the on-road testing and performance testing at the Transport Canada Test Centre, the vehicle was then tested for energy and emissions at Environment Canada’s Emissions Research and Measurement Division (ERMD) Laboratories located at the Environmental Technology Centre (ETC) in Ottawa, Ontario.

For the tests at ERMD, the vehicle was operated in battery-only mode and various hybrid modes on the CBD cycle, the Quebec City (QC) ÉcoloBus route, and other duties using a chassis dynamometer. Emissions measurements were analyzed, and general performance measurements were recorded. Results of these tests are presented in Table 22 and Table 23.

For the tests carried out at ERMD, it must be noted that the vehicle had been equipped with an additional Z5C ZEBRA battery, which had been placed on board to provide increased battery-only range. Therefore, the total on-board battery system comprised four batteries, totaling 71.2 kWh (rated) and approximately 140 kW (peak). The vehicle curb weight for these tests was approximately 6900 kg (15,200 lb.), but no other major changes were implemented.

The available power at the wheels was found to be sufficient to follow the CBD driving cycle appropriately. On the Quebec City route where road gradients over 12% were simulated, the bus was found to have difficulty moving from a dead stop when the incline was more than 6.5%. Difficulties with moderate grades were not expected based on calculations and were not seen in on-road testing by BET or in the Transport Canada performance testing, but difficulties on the higher road grades were expected.

Testing also showed that in battery-only mode, the vehicle loaded to about 50% of its payload capacity could travel 82 km on the simulated CBD drive cycle, and 69 km on the Quebec City route on a single battery charge and with auxiliaries (i.e., heat pump units) continuously operating. When adjusting for four batteries instead of three and the fact that the ERMD CBD cycle did not include an arterial cycle, these values are consistent with the third party performance testing, the on-road testing, and initial computer predictions. Total range in hybrid mode was not directly measured since the range is limited only by the size of the fuel reservoir.

The overall drivetrain efficiency was calculated from the ERMD data to be approximately 70%, with efficiencies during regenerative braking calculated to be 30% to 40%. These values were found by comparing dynamometer measurements with battery measurements. The dynamometer data, however, did not take into account the energy required to operate the heat pump units (and other auxiliary systems) that operated continuously at full capacity during the test. Auxiliary energy was not measured directly during testing, but accounting for a reasonable power draw (i.e., 7 kW) causes the correlation to the motoring efficiency to be above 90%, and the correlation to the regenerative braking efficiency to be about 80%. These adjusted efficiency values are comparable to the 86% efficiency calculated from the analysis following the initial computer modeling, as presented in Section 2.16.3.

Emissions data and fuel consumption for various hybrid scenarios are shown in Table 23. For hybrid tests in which the engine/generator was set to provide a constant output of about 30 to 35 kW (even during periods at zero speed), fuel consumption was calculated to be 38.1 L/100 km (6.2 mi./US gal.) for the CBD cycle. For hybrid tests in which the engine/generator provided a variable output dependent on the traction requirements, fuel consumption was calculated to be 32.7 L/100 km (7.2 mi./US gal.) for the CBD cycle. These values were significantly poorer (approximately 20% to 40%) than those obtained during the on-road testing. During all ERMD tests, however, the IC engine was never turned off but instead was left to continuously idle. Also, the ERMD tests ended with a net gain in battery state of charge (increase of approximately 14%), while the on-road tests ended with a net loss (approximately 19%). It is likely that these issues can account for the lower mileage obtained since the duty during on-road testing was somewhat similar to that of the CBD.

These values should also be viewed only as a starting point for this technology since the vehicle and systems tested were still in the prototype stage. A heavy, over-rated engine was used that was not controlled to the extent required, and the hybrid scenarios tested were not optimized. Use of a smaller engine and other hybrid power sharing strategies would allow improvement in mileage and emissions values. Since a corresponding bus with a conventional gasoline engine was not available to be tested, however, no direct comparison can be made.

**Table 22**
**EMRD Test Results vs. Performance Test Results, On-Road Test Results, and Computer Calculations**

| | EMRD Test Results | Performance Test Results | On-Road Test Results | Computer Calculations |
|---|---|---|---|---|
| **Range, Battery-Only Mode (single charge)** | 62 km for CBD cycle*<br>52 km for QC cycle* | 102 km at steady 50 km/h | 70 km in city drive | ≥ 80 km for light duty on flat roads |
| **Mileage, Hybrid Mode (L/100 km)** | 38.1 L/100 km for CBD, constant engine power<br>32.7 L/100 km for CBD, variable engine power | Not measured | 27.6 L/100km | ≤ 28 L/100 km<br>(≥ 10 mpg) |
| **Gradeability (%)** | Difficulties above 6.5% | 12% at 0 km/h<br>7% at 35 km/h | Measured to 7.3% | 12% at 0 km/h<br>7% at 35 km/h |

* Battery-only range values shown in this table were adjusted downward from reported values by ¾ to equate to a system of three batteries. Range values reported by ERMD were calculated based on use of 100% available battery energy (82 km for CBD Cycle; 69 km for QC route). Vehicle test weight = 7,711 kg (17,000 lb.) (Payload = 50% of capacity). Heat pump units in continuous, high-power operation.

**Table 23**
**Emissions Testing Results***

| Drive Mode | Drive Cycle | CO Carbon Monoxide (g/mile) | $CO_2$ Carbon Dioxide (g/mile) | NOx Oxides of Nitrogen (g/mile) | THC Total Hydrocarbon (g/mile) | Fuel Consumption (L/100 km) |
|---|---|---|---|---|---|---|
| Hybrid Mode with constant engine power | CBD | 33.6 | 1,408 | 21.4 | 6.6 | 38.1 |
| Hybrid Mode with variable engine power | CBD | 41.9 | 1,182 | 11.3 | 6.3 | 32.7 |

* All values shown are average over two drive cycles. Vehicle test weight = 7,711 kg (17,000 lb.) (Payload = 50% of capacity). Heat pump units in continuous, high-power operation.

# 9. DISCUSSION

## 9.1 Driver Expectations

The practical testing described in Section 8 proved that a viable multi-mode hybrid electric bus had been developed based on the OCC ELF configuration and using drive and powertrain components that were commercially available. Performance targets that had been established very early in the program were found to be attainable or were close to being achieved while still having developed a practical, working vehicle.

One issue that is less tangible and definable, however, is driver acceptance of the overall “feel” of the vehicle. The intent of the vehicle design is that drivers not encounter any unexpected responses from the vehicle.

Possible loss of traction power during driving is one of these issues. Normal ICE vehicles rarely have a complete loss of power during driving, and dashboard-warning lights are available to allow preemptive action. Any commercial electric or hybrid vehicle should attempt to meet this same expectation.

For hybrid operation, loss of traction power can take the form of loss of engine/generator power, or loss of battery power, or both. Loss of either the engine/generator or battery system will result in an immediate and unexpected reduction of available energy, and possibly power as well. Although not implemented on the prototype vehicle, dashboard-warning lights can be implemented to advise the driver that peak power and driving distance has been reduced if either system is lost. Unlike normal ICE vehicles, the two power systems of the multi-mode hybrid bus allow redundancy that limits the likelihood of a complete loss of power. This is clearly an advantage over ICE vehicles or pure electric vehicles.

At this point in the development of hybrid or electric vehicles, the probability of reduction or complete loss of power from the battery system is still significant. Cell failures within battery packs, battery pack degradation, or failure of battery control electronics will reduce with continued battery system development, production experience, and improved technologies. Battery SOC, however, is still largely under the control of the user, just as is the amount of gasoline in the fuel tank of any ICE vehicle. Complete loss of battery power will occur with any battery system if the battery SOC is allowed to drop too low. Also, for most battery electrochemistries, the amount of peak power tends to reduce as battery SOC drops, and individual cell losses at the time of failure aggravate this issue. This results in potential changes to vehicle power or performance while driving, especially for charge-depleting modes, which vehicle operators are not normally used to experiencing. Dashboard-warnings must be available to give drivers notification of battery SOC, or driving distance available, and this was implemented on the prototype bus in its later stage of development. Proper driver training is also a key issue.

One other issue that affects driver expectations of vehicle performance relevant to the prototype multi-mode shuttle was the configuration of the power available to the vehicle auxiliaries. The maximum power requirements for simultaneous operation of all of the auxiliary systems on board the bus totaled approximately 10 kW. The maximum amount of power available out of the battery system for the shuttle bus was approximately 90 kW (three ZEBRA batteries). Therefore, the control system was configured to allow no more than 80 kW to be delivered to the traction motor, thereby ensuring that 10 kW would always be available for auxiliary operation. This resulted in reduced performance under battery-only driving.

An alternative approach would be to supply the auxiliaries as needed, with the total remaining power being available for the traction motor. This approach, however, would result in a variation in available peak power depending on, for example, whether the heat pumps were being used for air conditioning. The system could also be developed to reduce or eliminate power to the auxiliaries when peak traction power is required. In this case, driver and passenger acceptance of dimming lights or drops in air conditioning power during vehicle accelerations or driving up hills must be addressed.

Overall, driver expectations will be dictated by the end-users, and any vehicles developed in the future by the project partners must retain enough flexibility to respond to user requests and requirements.

Commercial approaches for future vehicles will also include an optimization for a particular duty. The multi-mode approach used in this project helped investigate many hybrid power-sharing options, but this may not be a reasonable commercial approach. For applications where the duty cycle is well established, a single strategy could be employed. For example, for applications where battery-only drive is acceptable, the engine/generator system may be eliminated. Such grid-battery hybrid operations would likely require day-time charging along with the associated requirement for the driver (or other attendant) to make and remove the connection to the grid, as well as the associated repeated times throughout the day that the vehicle would not be in duty while it underwent charging. These requirements may limit grid-battery applications to specific niches. Hybrid vehicles with the engine/generator available as a back-up (whether needed or not) will likely still be the system architecture of choice by vehicle operators until grid-battery hybrid operation can be fully proven.

## 9.2 Emissions

This project was a development and learning exercise, with an aim to understanding and optimizing system efficiencies in hybrid electric drives. Therefore, specific emissions targets were not established up front. Clearly, the goal is to minimize emissions and maximize fuel economy while maintaining the vehicle performance targets, commercialization costs, and staying within the overall scope of the project.

The absolute prediction of emissions from hybrid buses under different driving and climate conditions is a complex issue. Although general statements can be made, these must be validated by experimental measurements on the operational vehicle.

Emission targets are also difficult to set since published data on emissions from hybrid vehicles is often difficult to interpret because driving patterns or technology levels are not clearly defined (e.g., driving pattern, route parameters, passenger loading, technology or maintenance level of the base vehicle, etc.,) making the basis for comparison a contentious issue. For example, a transit district may, quite legitimately, use its existing vehicles as the basis for comparison and they may be 15 to 20 years old. The hybrid vehicle will almost certainly have the latest engine technology, the latest engine management and post combustion systems, the engine will probably be smaller, and the vehicle structure will probably be lighter also. Measurements may show a 50% (for example) reduction in emissions (e.g., NOx, particulate, etc.). For such a transit district this comparison is reality. However, it may not be a true quantification of the unique contribution made possible by using electric drive components and energy storage in a battery.

Published emissions data from the 40 ft. New York City Orion Hybrid Bus, expressed relative to the CBD-14 cycle, are shown in Table 24. Although the level of the "Conventional Diesel" or "Conventional CNG" technology was not precisely defined, the data still offers a useful guideline and starting point for comparison.

Table 25 shows data from Californian sources for 40 ft. buses. Emissions for trolley and battery buses (grid-battery hybrids) take account of the balance and location of generating capacity and local fuel conditions. Battery buses would be better if only nighttime generating capacity were to be used.

It is not surprising that there is a large spread in the data shown and trying to extrapolate to the OCC shuttle is difficult. A more precise approach might be to compare a standard OCC diesel 28 ft. shuttle with the hybrid version operated in different hybrid modes under different simulated driving conditions. The information shown in Table 24 and Table 25 does offer an indication, however, of the magnitude of possible improvements.

**Table 24**
**Comparison of Fuel Economy and Emissions for New York City 40 ft. Buses**

| **Fuel Economy** | **Conventional Diesel** | **Conventional CNG** | **Orion Diesel Hybrid** |
|---|---|---|---|
| 40 ft. New York City bus (mi./US gal.) | 3.4 | 2.8 | 5.8 |

| **Emissions (g/mile)** | **CO** | **$CO_2$** | **NOx** | **PM** |
|---|---|---|---|---|
| Conventional Diesel | 5.2 | 2,984 | 31.50 | 0.660 |
| Conventional CNG | 9.0 | 2,483 | 20.80 | 0.025 |
| Orion Diesel Hybrid | 0.13 | 1,761 | 10.62 | 0.027 |

## Table 25
## Comparison of Emissions for California 40 ft. Buses

| | HC | CO | NOx | PM |
|---|---|---|---|---|
| **1985 Pre-DDEC Diesel Engine** | 3.49 | 8.62 | 36.62 | 1.65 |
| **New Diesel (DDEC)** | 1.99 | 5.08 | 20.32 | 0.93 |
| **Diesel with Trap** | 1.1 | 6.5 | 17.87 | 0.20 |
| **Methanol with Converter** | 1.72 | 22.3 | 10.70 | 0.28 |
| **Natural Gas with Converter** | 3.67 | 1.22 | 18.50 | 0.24 |
| **Trolley Coach (total)** | 0.14 | 0.34 | 3.49 | 0.19 |
| **Trolley Coach/Battery Bus (in basin)** | 0.09 | 0.15 | 0.37 | 0.02 |

# 10. CONCLUSIONS AND RECOMMENDATIONS

Overland Custom Coach, BET Services Inc., and Siemens, together with support from the Transportation Development Centre of Transport Canada via its own R&D budget and the available interdepartmental Program on Energy R&D (PERD) managed by NRCan, have developed a prototype energy-efficient, low-floor, multi-mode battery and hybrid electric 28 ft. bus for airport shuttle and some specialized transit applications.

The vehicle retained many of the characteristics of the OCC diesel ELF shuttle that was used as the base vehicle while also achieving the targeted 8,617 kg (19,000 lb.) GVWR. A Siemens drive system with a single 70 kW motor was successfully integrated with three parallel 17.8 kWh ZEBRA batteries from MES-DEA and a Ford 5.4 litre V8 gasoline/natural gas engine coupled to a Siemens generator.

All vehicle auxiliaries were successfully converted to electrical operation either through a 110 V AC system powered by an on-board inverter (including the power steering and power brakes, three roof-mounted heat pumps, and rear wheel suspension air compressor) or through the standard 12 V OEM system. Also, a low cost, lightweight, off-board high-power fast charging station was developed in conjunction with an on-board high-power inverter (70 kVA). This was in addition to a low power charging system installed on board the bus.

The vehicle and its sub-systems were modeled and tested on a dynamometer test bench developed at BET Services, and the completed vehicle was demonstrated on local roads in multi-mode operation, including driving the vehicle in battery-only mode, constant generation mode, and hybrid mode (with changing engine speed).

Due to the overall success of the project, the project partners are considering the development of future programs. Future investigations should include the following:

- Preparation of a more accurate cost analysis to describe the lifetime cost issue. This is important for fleet use commercial viability.
- Aggressive pursuit projects to build a reduced weight, thermally insulated bus to further reduce overall energy consumption.
- Follow-up projects that aim to build a low floor bus that is visually attractive (differentiation makes it easier to justify a premium).
- Exploration of replacing the Ford 5.4 litre engine used in the prototype vehicle with different, smaller engines, or a micro turbine (which are very clean). Replacement with hydrogen-based systems such as a hydrogen-burning engine or a simple fuel cell system operating in constant relatively low power mode would also help achieve the ultimate goal of a zero emission vehicle.
- Preparation of a business plan to exploit the lessons learned and work to create a Canadian-based assembly business for lightweight, user-friendly, reduced emissions commercial electric drive vehicles (buses and trucks).