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Hybrid Refuse Truck Feasibility Study

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by:

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Since some of the accepted measures in the industry are imperial, metric units are not always used in this report.

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16. Abstract

The objectives of this project were to explore the commercial viability of hybrid technology for urban refuse truck application, and to evaluate its environmental benefits. The study investigated the duty cycle of a typical truck operating on an urban route in Saint-Nicolas, Quebec. Hybrid powertrain architectures appropriate for this class of vehicle were identified and conceptual models were developed.

The studied options included parallel architectures and dual-mode series/parallel architectures. Both hydraulic and electric systems were investigated. Mathematical models of the selected systems were developed to simulate their performance and energy efficiency. The energy consumption of the systems was simulated using the Saint-Nicolas route data. The simulation included an analysis of vehicle curb weight reduction on energy efficiency. Based on the analysis of system efficiency, an economic model was developed to estimate the cost premium required to implement the technology and possible investment payback time.

The main conclusion of the study was that parallel systems offer efficiency improvement comparable to series systems at a much lower cost premium. Fuel and maintenance savings achievable using a hybrid system at current energy prices result in a payback time as low as four years. Hydraulic systems currently have a slight cost advantage over electric systems.

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16. Résumé

Ce projet avait pour objectifs d'examiner la viabilité commerciale d'un camion à ordures urbain à traction hybride, et d'évaluer les avantages d'un tel véhicule pour l'environnement. Les chercheurs ont caractérisé le cycle d'utilisation d'un camion à ordures type exploité sur un circuit urbain à Saint Nicolas, au Québec. Ils ont ensuite défini des architectures de motorisation convenant à cette classe de véhicules et élaboré des modèles conceptuels.

Les options envisagées comprenaient des architectures parallèle et des architectures bi-mode série-parallèle. Des systèmes hydrauliques et électriques ont été étudiés. Des modèles mathématiques des systèmes choisis ont été élaborés, afin de simuler leurs performances et leur efficacité énergétique. Pour simuler la consommation d'énergie, les caractéristiques du circuit de collecte de Saint-Nicolas ont été intégrées aux modèles. La simulation comprenait une analyse de l'effet de la réduction du poids à vide du véhicule sur son efficacité énergétique. À partir des données sur l'efficacité de chaque système, on a élaboré un modèle économique qui permet d'estimer les coûts supplémentaires à prévoir pour la mise en œuvre de la technologie, ainsi que le délai de récupération de l'investissement.

La principale conclusion de l'étude est que pour des gains d'efficacité comparables, les systèmes parallèle sont beaucoup plus économiques que les systèmes série. De plus, au prix actuel de l'énergie, un système hybride permet des économies de carburant et d'entretien conciliables avec un délai de récupération aussi court que quatre ans. Actuellement, les systèmes hydrauliques sont légèrement moins coûteux que les systèmes électriques.

17. Mots clés Camion à ordures urbain, groupe motopropulseur hybride, cycle d'utilisation, système parallèle, système série, bi-mode, hydraulique, électrique, ultra-condensateur, coûts supplémentaires, récupération des coûts	18. Diffusion Le Centre de développement des transports dispose d'un nombre limité d'exemplaires.

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EXECUTIVE SUMMARY

Urban refuse collection is a major industry in North America, with a fleet estimated at approximately 200,000 vehicles. U.S. refuse trucks use 1 billion gallons of diesel fuel annually, representing 3 percent of the country's total diesel fuel consumption. Increasing fuel costs and environmental concerns drive efforts to develop cleaner, quieter, more productive and more energy efficient refuse trucks.

The objectives of this project were to explore the commercial viability of hybrid technology for urban refuse truck application, and to evaluate its environmental benefits. The scope of the project included a technical analysis of existing and potential hybrid system architectures via simulation of their performance and energy consumption, as well as an economic analysis of hybrid technology implementation.

A refuse truck operates on urban collection routes, making up to 150 stops per hour. This operating mode imposes heavy loads on the powertrain and results in very poor fuel efficiency and high emissions. Hybrid powertrains perform well in such conditions, and in recent years a number of initiatives have been launched to explore the potential of hybrid systems for refuse truck propulsion. In Europe, French truck manufacturer PVI offers a dual-mode hybrid electric refuse truck with an electric drive for refuse collection mode and a conventional powertrain for street driving. Swedish company Renova operates trucks with electric refuse handling systems. In North America, hybrid refuse trucks are not available commercially. Several companies are working on hydraulic hybrid technology for refuse trucks, including Eaton, Dana, the U.S. Environmental Protection Agency and Fiba Canning. Heavy duty electric hybrid powertrains for trucks and buses are available from Allison, BAE/Orion, ISE Research and several other companies. Some of those systems can potentially be adapted for refuse trucks.

The maximum benefits of a hybrid powertrain are realized when the system is designed for the specific duty cycle of the vehicle. In the case of the refuse truck, the duty cycle consists of approximately 76 percent of time collecting the refuse; 20 percent of time in transfers between the depot, collection route and the landfill; and the remaining 4 percent of time unloading the truck. The vast majority of fuel is consumed in collection mode, where the vehicle is much less efficient due to the high energy expenditure in operating the hydraulic refuse handling equipment. The amount of fuel consumed to generate hydraulic power represents approximately 40 percent of the total fuel consumed in collection mode.

The choice of hybrid technology and powertrain architecture for refuse trucks remains open. The presence of a complex hydraulic system for refuse handling enables relatively easy integration of a hydraulic hybrid powertrain. On the other hand, electric hybrid systems are more flexible, have smaller volume, and in the long term may be cheaper than hydraulic systems. The architecture of the system is similar for both electric and hydraulic systems. In the simplest parallel system, the electric or hydraulic motor is coupled with the drive shaft and provides torque assist to the engine. In a hydraulic system, it is also possible to use the hydraulic pump in parallel configuration to recover braking energy to support the hydraulic equipment rather than for torque assist. Due to the two distinct operating modes – collection and transfer – it is possible to build a dual mode system in which the powertrain operates as series hybrid in collection mode and a parallel system in transfer mode. The most advanced option is a series-parallel configuration that adjusts its operation mode depending on vehicle speed and engine load. At low speeds, the vehicle operates in electric-only mode, at medium speeds as a series hybrid and at high speeds as parallel hybrid. This option has been selected by Allison for its heavy duty hybrid transmission for trucks and buses.

Analysis of performance characteristics of various hybrid system architectures identified the hybrid system component size required to meet performance criteria set for conventional refuse trucks. The baseline vehicle assumed for the analysis was a 25,500 kg GVW Labrie model built on an Autocar chassis with a 320 hp Cummins ISM engine. The study indicated that the minimum motor size for an electric parallel system is approximately 90 kW. This is sufficient to fully recover braking energy on a typical route and to provide a torque boost during low speed acceleration, improving the acceleration time to 20 km/h by 1 second. A dual-mode electric hybrid system requires a minimum 150 kW traction motor to provide acceleration comparable to a conventional truck. The dual mode electric system also requires a 120 kW generator to achieve efficient operation. The hydraulic parallel system requires a 130 cm^3/rev hydraulic pump to recover the braking energy. The hydraulic dual-mode system requires a 250 cm^3/rev motor and 130 cm^3/rev pump to achieve the performance of the baseline vehicle. Energy storage in the electric system poses a substantial challenge due to the high frequency of discharge. A battery pack built using existing technologies would need to be relatively large to withstand the high power pulses, and its durability would be limited to less than two years. Ultracapacitor technology appears to be most appropriate for this application because of its significantly higher cycle life. The refuse truck's duty cycle is characterized by high power demand and relatively low energy demand. The energy needs on a typical route are under 600 Wh at a peak power of up to 200 kW. This falls well within the limits of existing ultracapacitor products. For hydraulic systems, pressure accumulators of that size are commercially available and represent mature technology.

The results of the performance analysis were the starting point to develop conceptual models of typical hybrid system architectures. The simulation models were built using Matlab/Simulink® software, and a number of system options were investigated using the data from a collection route in Saint-Nicolas, Quebec. The duty cycle data were provided by Équipement Labrie, a Quebec-based refuse truck manufacturer, and are representative of a modern side-loading refuse truck. The simulated systems included the baseline conventional vehicle, a parallel electric hybrid, a dual-mode electric hybrid, a parallel hydraulic hybrid (with engine assist and equipment assist options) and a dual-mode hydraulic hybrid. Each model was subject to basic optimization to ensure that it represented the most efficient system possible within the limitation of the model.

The fuel efficiency of each system was simulated using the Saint-Nicolas route speed profile, with vehicle payload increasing until the gross vehicle weight was achieved.

The results of the simulation indicated that the electric parallel and the dual-mode electric systems achieve similar fuel savings potential, approximately 18 percent. The parallel hydraulic system in torque assist configuration provided 11 percent fuel savings and the dual-mode hydraulic system, 9 percent. The parallel hydraulic system in pressure assist configuration turned out to be the best option, with 19 percent fuel savings. The fuel consumption reduction was low relative to other heavy duty applications that can achieve up to 40 percent fuel savings. This is due to the fact that traction accounts for only 60 percent of the refuse truck's fuel consumption. If the simulation results were prorated for the traction share only, the fuel savings percentages would be in the order of 30 to 35 percent for the most efficient systems. It must be noted that the results presented in this report are based on rather conservative assumptions; well-engineered production systems are likely to achieve somewhat higher efficiency, possibly up to 25 percent. The 20 to 25 percent fuel consumption savings possible through hybridization represent 8 to 10 L of fuel saved per single payload. Curb weight reduction can further improve fuel consumption by approximately 0.5 to 0.8 L of fuel per payload per 1000 kg weight reduction.

An important benefit of the hybrid option is a significant reduction of exhaust gas emissions. For parallel systems, the emissions reduction is proportional to the reduction in fuel consumption. For dual-mode systems, greenhouse gas emissions reduction is in line with the fuel consumption reduction, while ozone-forming components and particulate matter can be reduced by as much as 90 percent. Assuming a 25 percent reduction in fuel consumption achievable using hybrid technology, it is possible to reduce annual carbon dioxide emissions from a single truck by approximately 13 metric tons (equivalent to 5000 L of saved diesel fuel). If the entire refuse truck fleet in Canada could be converted to achieve similar fuel efficiency, the annual reduction in greenhouse gas emissions would amount to approximately 200,000 metric tons.

The economic analysis of hybrid refuse truck viability accounted for the cost of the additional components, development costs and increased labour to integrate the system into the vehicle. The cost analysis indicated that the cost premium for near-term volume production can be estimated at approximately US$22,000 for both hydraulic and electric parallel systems. The additional cost for an electric dual-mode system would be US$53,000 and the dual-mode hydraulic system would cost an extra US$26,000. Assuming the average fuel price during the payback period at current levels of US$0.70/L, the payback time for the parallel systems would be just under 5 years (4.9 for electric system and 4.7 for hydraulic pressure assist). For dual-mode electric and dual-mode hydraulic systems, payback time would be 11 and 8 years, respectively. At US$0.80/L, the current California price, the payback time for a parallel system would be reduced to approximately 4 years. It is highly probable that future fuel prices will be significantly higher than today, further shortening the payback time.

Comparison of the technologies and system configurations indicates that parallel systems are the viable solution in the near term, providing up to 25 percent fuel consumption savings and a similar level of emissions reduction, while offering a reasonable payback time. Due to the nature of the vehicle and the duty cycle, it is unlikely that dual-mode systems can achieve significantly higher efficiency than parallel systems, although it is possible that they may achieve substantially better emissions and noise characteristics. The high premium for dual-mode systems can be only justified if there is a measurable incentive to dramatically reduce noise and emissions.

The results of the study indicate that hydraulic systems have lower energy efficiency than advanced electric systems. However, lower cost and simpler implementation of the hydraulic hybrids results in shorter payback time than for electric systems. Hydraulic components are readily available mature products, while electric components for heavy duty vehicles are still in small volume production and have not yet achieved the maturity level of hydraulic components. From the standpoint of near-term application, a simple hydraulic parallel system in pressure assist configuration seems to be the most viable option. However, a parallel electric configuration has the potential of matching the efficiency and cost of the parallel hydraulic system in the near future. In the longer term, electric systems may offer lower costs than hydraulic systems, while providing additional benefits such as better performance, lower noise, simpler packaging, and reduction of hydraulic equipment load by an electrically driven pump.

SOMMAIRE

La collecte des ordures ménagères dans les villes est une industrie importante en Amérique du Nord, où on estime le parc de bennes à ordures à environ 200 000. Aux États-Unis, les camions à ordures consomment 1 milliard de gallons de diesel par année, ce qui représente 3 p. 100 de la consommation totale de carburant diesel dans ce pays. La spirale ascendante du prix du carburant et le souci de l'environnement stimulent les recherches en vue de mettre au point des camions à ordures plus propres, plus silencieux, plus productifs et plus éconergétiques.

Ce projet avait pour objectifs d'examiner la viabilité commerciale d'un camion à ordures urbain à traction hybride, et d'évaluer les avantages d'un tel véhicule pour l'environnement. Des méthodes de simulation ont servi à analyser les performances et la consommation d'énergie de diverses architectures existantes et possibles de motorisation hybride. La technologie hybride a également été analysée d'un point de vue économique.

Un camion à ordures qui parcourt un circuit de collecte urbain peut faire jusqu'à 150 arrêts à l'heure. Ce mode de fonctionnement est non seulement très exigeant pour le groupe motopropulseur, mais il entraîne également une forte consommation de carburant et de hauts niveaux d'émissions. Or, les groupes motopropulseurs hybrides sont particulièrement bien adaptés à ces conditions. C'est pourquoi les projets visant à explorer la possibilité de munir les camions à ordures ménagères de systèmes hybrides se sont multipliés ces dernières années. En Europe, PVI, le constructeur de camions français, offre une benne à ordures ménagères hybride électrique bi-mode, dotée d'une traction électrique pour la collecte des ordures et d'un groupe motopropulseur classique pour la conduite dans les rues. L'entreprise suédoise Renova exploite des camions munis de systèmes électriques de manutention des ordures. En Amérique du Nord, on ne trouve pas encore de camions à ordures hybrides sur le marché. Plusieurs groupes sont à développer une technologie hybride hydraulique pour les camions à ordures, dont Eaton, Dana, l'EPA (Environmental Protection Agency) des États-Unis et Fiba Canning. Des groupes motopropulseurs électriques hybrides renforcés pour camions et autobus sont offerts par Allison, BAE/Orion et ISE Research, entre autres. Certains de ces systèmes pourraient être adaptés pour motoriser des camions à ordures.

Pour tirer le maximum d'avantages d'un groupe motopropulseur hybride, il faut que celui-ci soit conçu en fonction du cycle d'utilisation spécifique du véhicule. En l'occurrence, un camion à ordures passe environ 76 p. 100 de son temps de fonctionnement à ramasser les ordures et 20 p. 100, à se déplacer entre le garage, le circuit de collecte et la décharge. Les 4 p. 100 qui restent représentent le temps de déchargement du camion. C'est donc en mode *collecte des ordures* que la plupart du carburant est consommé et que le véhicule est le moins efficace, du fait de la grande quantité d'énergie nécessaire pour faire fonctionner l'équipement hydraulique de manutention des ordures. Ainsi, environ 40 p. 100 du carburant consommé en mode *collecte* sert à produire de l'énergie hydraulique.

Il reste à déterminer la technologie hybride et l'architecture du groupe motopropulseur convenant le mieux aux camions à ordures. Certes, la présence d'un système hydraulique complexe pour la manutention des ordures permettrait une intégration relativement facile d'un groupe motopropulseur hydraulique hybride. Mais les systèmes électriques hybrides sont plus souples et moins encombrants et pourraient, à la longue, se révéler moins coûteux que les systèmes hydrauliques. Les deux systèmes présentent des architectures semblables. Dans l'architecture parallèle la plus simple, le moteur, électrique ou hydraulique, est engrené sur l'arbre de transmission et augmente le couple du moteur. Dans un système hydraulique, il est aussi possible d'utiliser la pompe hydraulique montée en parallèle pour récupérer l'énergie de freinage et assister l'équipement hydraulique plutôt qu'augmenter le couple. Compte tenu des deux modes de fonctionnement du véhicule – mode *collecte* et mode *déplacement* – un système bi-mode est envisageable, dans lequel le groupe moteur fonctionne en série pour le mode *collecte* et en parallèle pour le mode *déplacement*. L'option la plus évoluée est une configuration série-parallèle qui s'adapte d'elle-même au mode de fonctionnement, selon la vitesse du véhicule et la charge du moteur. Aux faibles vitesses, le véhicule est tout électrique, aux vitesses moyennes, il utilise une configuration hybride série et aux grandes vitesses, une configuration hybride parallèle. C'est cette dernière option qu'a retenue Allison pour sa transmission hybride renforcée pour camions et autobus.

L'analyse des performances des diverses architectures de systèmes hybrides a permis de dimensionner les composants d'un système hybride en fonction des critères de performance exigés des camions à ordures classiques. Le véhicule de référence utilisé pour l'analyse était un modèle Labrie de 25 500 kg de poids à vide construit sur un châssis Autocar et doté d'un moteur Cummins ISM de 320 hp. L'étude a révélé que pour un système électrique parallèle, la puissance du moteur doit être d'environ 90 kW. Cela suffit pour récupérer pleinement l'énergie de freinage sur un circuit normal et augmenter le couple au cours d'une accélération lente, réduisant d'une seconde le temps d'accélération jusqu'à 20 km/h. Un système électrique hybride bi-mode exige un moteur de traction d'au moins 150 kW pour assurer une accélération comparable à celle d'un camion diesel classique. Le système électrique bi-mode exige également un générateur de 120 kW pour un bon rendement. Le système hydraulique parallèle exige une pompe hydraulique de 130 cm^3/rev pour récupérer l'énergie de freinage. Le système hydraulique bi-mode exige un moteur de 250 cm^3/rev et une pompe de 130 cm^3/rev pour atteindre les performances du véhicule de référence. Le stockage de l'énergie dans le système électrique représente un défi majeur, en raison des décharges fréquentes. Un bloc-batterie qui utiliserait les technologies existantes devrait être relativement gros pour résister aux fortes impulsions d'énergie, et sa durabilité ne dépasserait pas deux ans. La technologie des ultra-condensateurs semble être celle qui convient le mieux à cette application, en raison de sa durée de vie (cycles de charge/décharge) de beaucoup supérieure. Le cycle d'utilisation des camions à ordures se caractérise par une forte demande de puissance combinée à une demande d'énergie relativement faible. Ainsi, sur un circuit représentatif, les besoins en énergie sont inférieurs à 600 Wh à une puissance de pointe qui peut atteindre 200 kW. Ces valeurs sont bien en-deçà des limites des ultra-condensateurs existants. Pour les systèmes hydrauliques, les accumulateurs de pression de cette taille existent en tant que produits standard sur le marché.

Les résultats de l’analyse des performances ont été le point de départ de l’élaboration de modèles conceptuels d’architectures de systèmes hybrides types. Des modèles de simulation, construits à l’aide du logiciel Matlab/Simulink® et auxquels avaient été intégrées les données relatives à un circuit de collecte situé à Saint-Nicolas, au Québec, ont été appliqués à divers systèmes. Les données sur le cycle d’utilisation, fournies par Équipement Labrie, un constructeur de camions à ordures du Québec, sont caractéristiques d’un camion à ordures moderne à chargement latéral. Les systèmes simulés comprenaient le véhicule de référence classique, un hybride électrique parallèle, un hybride électrique bi-mode, un hybride hydraulique parallèle (avec options *assistance du moteur* et *assistance des accessoires*) et un hybride hydraulique bi-mode. Chaque modèle a été sommairement optimisé pour représenter le meilleur rendement possible des systèmes à l’intérieur des limites imposées par le modèle.

La consommation de carburant de chaque système a été simulée d’après le profil des vitesses mesurées le long du circuit de collecte de Saint-Nicolas, la charge utile augmentant jusqu’à ce que le poids nominal brut du véhicule soit atteint. Selon les résultats de cette simulation, le système électrique parallèle et le système électrique bi-mode génèrent des économies de carburant semblables, d’environ 18 p. 100. Le système hydraulique parallèle en configuration *addition du couple* a généré des économies de carburant de 11 p. 100, et le système hydraulique bi-mode, de 9 p. 100. Le système hydraulique parallèle en configuration *addition de pression* s’est révélé l’option la plus intéressante, avec des économies de carburant de 19 p. 100. L’économie de carburant était faible, comparativement aux autres applications pour poids lourds, qui peuvent entraîner des économies pouvant aller jusqu’à 40 p. 100. Cela est dû au fait que pour un camion à ordures, la traction ne représente que 60 p. 100 de la consommation de carburant. Si les résultats de la simulation étaient appliqués au prorata de la portion *traction* seulement, les pourcentages d’économie de carburant seraient de l’ordre de 30 à 35 p. 100 dans le cas des systèmes les plus efficaces. Il convient de noter que les résultats présentés ici sont fondés sur des hypothèses passablement prudentes; des systèmes d’exploitation bien conçus sont de nature à générer des économies plus importantes, qui peuvent atteindre 25 p. 100. Les économies de carburant de 20 à 25 p. 100 offertes par la technologie hybride représentent une économie de 8 à 10 L de carburant pour une pleine charge utile. Enfin, une réduction de 1 000 kg du poids à vide du véhicule peut aussi entraîner une baisse de 0,5 à 0,8 L de la consommation de carburant par charge utile.

L’un des avantages marquants de l’option hybride réside dans la diminution importante des émissions de gaz d’échappement. Dans le cas des systèmes parallèles, la diminution des émissions est proportionnelle à la diminution de la consommation de carburant. Pour ce qui est des systèmes bi-mode, la diminution des émissions de gaz à effet de serre est conforme à la diminution de la consommation de carburant, tandis que la présence de composantes ozonogènes et de particules fines peut diminuer jusqu’à 90 p. 100. En supposant une diminution de 25 p. 100 de la consommation de carburant réalisable grâce à l’utilisation de la technologie hybride, il est possible de réduire la quantité d’émissions de dioxyde de carbone produites annuellement par un camion d’environ 13 tonnes métriques (soit l’équivalent d’une économie de 5 000 L de carburant diesel. Dans l’éventualité où la totalité du parc de camions à ordures au Canada pourrait être convertie afin d’atteindre un rendement en carburant semblable, la diminution annuelle des émissions de gaz à effet de serre s’élèverait à quelque 200 000 tonnes métriques.

Pour l’analyse économique de la viabilité des camions à ordures hybrides, on a tenu compte du coût des composants additionnels, des coûts de développement et de la main-d’œuvre nécessaire pour intégrer le système dans le véhicule. Cette analyse a révélé que, à court terme, le coût supplémentaire associé à un système électrique ou hydraulique parallèle pouvait être estimé à environ 22 000 $US. Dans le cas d’un système électrique bi-mode, le coût supplémentaire s’établirait à 53 000 $US, tandis que le système hydraulique bi-mode coûterait 26 000 $US de plus que le véhicule de référence. En supposant que le prix moyen du carburant se situerait aux niveaux actuels, soit autour de 0,70 $US/L pendant le délai de récupération, ce délai serait d’un peu moins de cinq ans pour les systèmes parallèle (4,9 pour le système électrique et 4,7 pour le système hydraulique à addition de pression). Pour les systèmes électrique et hydraulique bi-mode, le délai de récupération serait de 11 ans et de 8 ans, respectivement. À 0,80 $US/L, le prix actuel du carburant en Californie, le délai de récupération pour un système en parallèle ne serait plus que de 4 ans environ. Il est très probable que dans l’avenir, le prix du carburant sera beaucoup plus élevé que maintenant, ce qui raccourcira d’autant le délai de récupération.

La comparaison des technologies et des configurations possibles révèle que les systèmes parallèle sont la solution viable à court terme, car ils offrent jusqu’à 25 p. 100 d’économie de carburant et un pourcentage semblable de réduction des émissions, tout en faisant entrevoir un délai de récupération raisonnable. En raison de la nature du véhicule et de son cycle d’utilisation, il est peu probable que des systèmes bi-mode puissent être plus efficaces que les systèmes parallèle, mais ils pourraient bien se révéler de beaucoup supérieurs sur le plan des émissions et du bruit. Les coûts beaucoup plus élevés associés aux systèmes bi-mode ne peuvent se justifier que s’il existe une incitation financière à réduire de façon importante le bruit et les émissions.

Selon les résultats de l’étude, les systèmes hydrauliques sont moins éconergétiques que les systèmes électriques évolués. Toutefois, comme ils sont moins coûteux et plus simples à mettre en œuvre que les systèmes électriques, ils entraînent un délai de récupération plus court. Les composants hydrauliques sont des produits standard qu’il est facile de se procurer sur le marché, tandis que les composants électriques pour poids lourds sont encore produits en faibles volumes et n’ont pas encore atteint le degré de maturité des composants hydrauliques. Pour une application à court terme, un simple système hydraulique parallèle en configuration *addition de pression* semble être l’option la plus viable. Toutefois, il se pourrait bien que dans un proche avenir, une configuration électrique parallèle présente la même efficacité que le système hydraulique parallèle, à un coût semblable. Avec le temps, les systèmes électriques pourraient devenir moins chers que les systèmes hydrauliques, tout en offrant des avantages supplémentaires, comme de meilleures performances, moins de bruit, un conditionnement simplifié, et une diminution de la charge de l’équipement hydraulique, grâce à une pompe électrique.

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TABLES

GLOSSARY

AMT	Automatic Manual Transmission
ARC	Automotive Research Center
ATX	Automatic Transmission
BAT	Battery
BSFC	Brake Specific Fuel Consumption
CARB	California Air Resources Board
CNG	Compressed Natural Gas
ENG	Engine
EPA	Environmental Protection Agency
ETA	Electric Torque Assist
EDM	Electric Dual-mode
GEN	Electric Generator
GB	Gear Box
GVW	Gross Vehicle Weight
HDM	Hydraulic Dual-mode
HLA	Hydraulic Launch Assist
HM	Hydraulic Motor
HP	Hydraulic Pump
HPA	Hydraulic Pressure Assist
HTA	Hydraulic Torque Assist
ICE	Internal Combustion Engine
IMA	Integrated Motor Assist
IMG	Integrated Motor-Generator
ISG	Integrated Starter-Generator
MG	Electric Motor-Generator
MOT	Electric Motor
NREL	National Renewable Energy Laboratory
OEM	Original Equipment Manufacturer
PA	Pressure Accumulator
PG	Planetary Gear
RDS	Regenerative Drive System
UC	Ultracapacitor
ZEV	Zero Emission Vehicle

1. INTRODUCTION

1.1 Industry Profile

Urban refuse collection is a major industry in North America, employing over 300,000 people. Its revenues approach US$50 billion. The industry is also a significant energy consumer. In the United States refuse trucks use 1 billion gallons of diesel fuel annually, representing 3 percent of the country's total diesel fuel consumption. The U.S. fleet of refuse trucks comprises 179,000 vehicles, including 136,000 garbage trucks, 12,000 transfer vehicles and 31,000 dedicated recycling vehicles [1]. The combined North American refuse truck fleet is estimated at approximately 200,000 vehicles.

The main factors driving innovation in the industry are:

- Operating cost reduction – Refuse trucks have the worst fuel economy among urban commercial vehicles. Increasing fuel costs drive the efforts to implement more energy efficient technologies.

- Productivity – Improving vehicle productivity leads to savings in equipment and labour costs. Automatic side loaders are a fast growing sector of the industry thanks to their substantially higher throughput compared to rear loaders (up to three times more productive and require only one operator). Automatic loaders operate in a very intense stop-and-go mode that imposes additional demands on the vehicle's powertrain and its hydraulic system. Vehicle acceleration is a critical factor in increasing the number of possible stops per hour.

- Emissions – Refuse trucks are a highly visible source of urban air pollution. The majority of them (over 90 percent) are diesel-fuelled, with a steadily growing Compressed Natural Gas (CNG) vehicle share. Concerns about health effects of diesel particulates, combined with the issues of greenhouse gas emissions, have resulted in growing pressure to reduce the environmental impact of these vehicles. The California Air Resources Board (CARB) has recently passed a law to regulate the refuse trucks in the state with an objective to reduce their emissions. The regulation requires refuse truck owners (13,000 trucks in California) to reduce the vehicles' particulate matter emissions by 85 percent (compared to 2000 levels) by 2015 [2]. As with the case of the now-defunct Zero Emission Vehicle (ZEV) mandate for light vehicles, the CARB initiative has already sparked a number of activities to develop cleaner and more energy efficient technologies.

- Noise – Acoustic emissions reduction is a major issue for the industry as the current trucks tend to be noisy and operate in residential areas. The high noise levels also pose health issues for the truck operators. A significant noise reduction is perceived as a definite marketing advantage for an alternative drive system.

1.2 Refuse Truck Characteristics

Most refuse trucks fall into the Class 8 weight category, which includes the heaviest vehicles with a Gross Vehicle Weight (GVW) of over 14,983 kg (33,001 lb.). The refuse trucks are typically based on a three-axle truck chassis and their GVW is up to 29,483 kg (65,000 lb.).

Typical refuse truck designs fall into one of the following categories [3]:

- Rear loader – the most common conventional design loaded manually from the rear
- Front loader – a popular design for loading large containers
- Side loader – a vehicle for residential collection loaded from the side, manually or automatically
- Recycling unit – dedicated truck with separate compartments for various recycled materials

Refuse truck powertrains are based on Original Equipment Manufacturers (OEM) Class 8 platforms, typically up to 320 hp, often oversized to account for the extra heavy duty operation. As a result, the large engines operate during a significant portion of the duty cycle at very low loads. A unique aspect of the refuse truck application is also its high power demand for the hydraulic equipment for refuse handling. The engine load imposed by the main hydraulic pump is typically at idling speed conditions, resulting in a significant portion of the total fuel consumed by the hydraulic system.

1.3 Refuse Truck Hybridization Issues

The intensive stop-and-go duty cycle of refuse trucks makes them a natural application for hybrid propulsion. The side loading automatic system, operating with up to 1200 stops per day, is a particularly suitable candidate for hybridization. Recent emergence of commercial hybrid drives for heavy duty trucks and buses has reduced the cost and widely improved the availability of components, particularly for hybrid electric systems. At the same time, fuel prices have increased sharply and remain on the upward trend, creating a realistic commercial opportunity for heavy duty hybrid systems.

The viability of a hybrid refuse truck is based primarily on its economics compared with that of a conventional system. The fuel and maintenance savings must be sufficient to offset the vehicle cost premium within a reasonable payback time, potentially two to three years. The emissions reduction potential of the hybrid system may also have a measurable effect on the payback time if a portion of the cost can be passed on to the consumer through government initiatives such as CARB regulations in California. Finally, the non-quantifiable benefits of a hybrid system, such as lower noise emissions, improved performance, and a better working environment, should be factored in to assess the appeal of the hybrid technology versus diesel and CNG options.

1.4 Project Goals

The objectives of this project were to explore the viability of hybrid technology in the context of urban refuse truck application and to evaluate the potential benefits of the technology in terms of direct cost savings to the end user, as well as the environmental benefits such as lower energy consumption, emissions and noise.

The scope of the project included evaluation of existing technologies for heavy duty commercial vehicles, analysis of possible hybrid system architectures, simulations of performance and energy efficiency of selected systems, and cost/benefit analysis of the technology.

2. TECHNOLOGY STATUS

2.1 Literature Survey

Although several hybrid refuse truck prototypes have been demonstrated to date, the number of available references related to refuse truck technology and its duty cycle is relatively modest.

The duty cycle of a refuse truck was addressed in a study by West Virginia University exploring the commercial vehicle environment in New York City [4]. The study introduced the New York City refuse truck duty cycle, composed of 8 micro-cycles separated by periods for loading and compacting the refuse. The NYC Garbage Truck cycle has been an only reference for hybrid truck simulation to date.

Recent work conducted by the Automotive Research Center (ARC) [5] to develop a statistically representative duty cycle for a refuse truck is a major step toward a standardized cycle. The project involved detailed measurement of refuse truck operating parameters on multiple routes in six cities. The authors conducted an extensive statistical analysis of the test data in an attempt to develop a duty cycle that would best represent the operating environment of a refuse truck. Such a standard cycle would be a valuable tool to evaluate the performance of various systems under controlled conditions. However, detailed results of the study have not been published yet.

A study of a refuse truck operating on an urban route in the UK, conducted by Ricardo [6], discusses potential energy savings possible using hybrid drives. The study compares the energy efficiency of a typical refuse truck on different duty cycles, including standard cycles as well as a cycle based on data measured for the truck operating on the actual refuse collection route. The results obtained for the measured cycle are most representative of the actual truck operation, as the standard cycles developed for trucks and buses are substantially different. The study identifies the hydraulic parallel systems (launch assist) as the most efficient options, improving fuel economy by 50 percent. A parallel electric system is reported to improve fuel economy by 32 percent and a series electric system by 26 percent. Based on these fuel economy figures, the amount of fuel saved on the route is 33 percent, 24 percent and 21 percent, respectively.

2.2 Electric Hybrid Refuse Trucks

Electric and dual-mode hybrid electric trucks have been in operation in Europe for several years. European trucks use electric power for low speed traction and the auxiliary systems for loading and compacting the refuse. Although the approach does reduce noise and improve fuel efficiency, it does not have adequate performance to offer a substitute for conventional diesel or CNG trucks operated in North America.

The examples of hybrid electric refuse truck systems are PVI and Renova.

PVI

PVI, a French manufacturer of special purpose vehicles, offers a hybrid refuse truck based on a Renault Puncher platform. The Puncher Bimode vehicle operates on the highway as a conventional vehicle but uses an electric drive in collection mode. The prime mover is a 265 hp Renault VI common-rail diesel engine. The 36 kW traction motor is powered by a 96 V, 900 Ah battery pack. The hydraulic system is driven by a 12 kW motor powered from the main battery pack. The vehicle is also available in all-electric mode with a larger 1680 Ah battery [7].

Renova

Based in Goeteborg, Sweden, Renova operates a fleet of 125 refuse trucks. The company has 15 trucks with an electric power system for hydraulic compaction. The battery pack is charged by the engine during operation and can be charged at night from an outlet. The traction drive is conventional (CNG or biogas) but equipped with an anti-idling system that turns off the engine 30 seconds after the driver gets out of the vehicle [8].

2.3 Electric Hybrid Trucks and Buses

Heavy duty electric hybrid powertrains have been commercially available for transit buses since the mid-1990s. Transit buses belong to the same weight class as refuse trucks and operate in similar conditions. Consequently, hybrid powertrains used in transit buses can be adapted for hybrid refuse trucks. The main suppliers of heavy duty electric hybrid drives are GM Allison, BAE/Orion and ISE Research. Smaller companies, which are also capable of heavy duty electric hybrid systems integration, include Azure Dynamics, Enova Systems, Oshkosh Truck Corporation and Hybrid Bus Technologies.

GM Allison

Allison is currently the only company that offers a commercial parallel-series drive for heavy duty applications. The company calls the system “a two-mode compound split parallel hybrid". The Allison unit consists of two 100 kW AC induction electric machines and an automatic transmission mechanism integrated into a package the size of a conventional transmission. The power is supplied by a 600 V NiMH battery pack. The system can be coupled with diesel engines rated 280 hp continuous (model EV40) or 330 hp continuous (model EV50) [9].

Orion/BAE

BAE has been building hybrid drives for Orion transit buses since 1998 and now has its third generation of the system in the Orion VII bus. The Orion VII series hybrid powertrain consists of a 260 hp Cummins 5.9 ISB diesel engine coupled with a 120 kW permanent magnet generator. The AC induction traction motor delivers 250 hp continuous, 320 hp intermittent power. The lead acid battery pack operates at nominal 580 V [10].

ISE Research

San Diego-based ISE has developed the ThunderVolt gasoline-electric series hybrid system based on Ford's ULEV V-10 Triton 6.8 l engine. The system uses a 150 kW generator and two 85 kW (114 hp) traction motors by Siemens. The hybrid buses built by ISE can travel up to 24 km (15 mi.) in electric mode and claim 30 percent regeneration of daily operating energy [11].

Azure Dynamics

Canadian company Azure Dynamics has developed a range of traction motors that can be applied to heavy duty applications. The AC90 motors developed by Azure are used in heavy duty series and parallel hybrid systems for delivery vehicles and shuttle buses. The company has the capability to integrate an electric hybrid powertrain for a refuse truck using in-house developed components, including ultracapacitor packs [12].

Enova Systems

California-based Enova's heavy duty series hybrid drive uses a 2.5l TD engine coupled with a 60 kW generator and one or two 120 kW (161 hp) traction motors [13].

Oshkosh Truck Corporation

Wisconsin's Oshkosh is developing a series hybrid electric system for Class 7-8 applications under contract from National Renewable Energy Laboratory (NREL). The system has a 110 kW traction motor powered by an ultracapacitor or NiMH battery pack [14].

Hybrid Bus Technologies

The Denver-based company's series hybrid powertrain for 14 m (45 ft.) buses uses a CNG engine and a 100 kW PM generator from UQM Technologies. The traction power is supplied by two UQM 100 kW motors [15].

2.4 Hydraulic Hybrid Technology

A unique feature of refuse trucks is their on-board hydraulic system for trash collection and compaction. The availability of hydraulic power opens the possibility of using a hydraulic system, and most of the recent research is focused on that technology. There are no commercial hydraulic hybrid systems on the market yet, although several demonstration projects are under way. Developers of hydraulic hybrid systems include the Eaton Corporation, Dana, the U.S. Environmental Protection Agency (EPA) and Ontario-based Fiba Canning.

Eaton Corporation

Eaton has developed a parallel hydraulic hybrid system called Hydraulic Launch Assist (HLA). The light-duty version of the system was first demonstrated in January 2002 in the Ford Mighty F-350 Tonka concept pick-up truck. The Tonka HLA system reportedly recovers as much as 80 percent of the braking energy and can propel the truck up to 48 km/h without the engine contribution [16].

A heavy duty HLA system was developed in 2004 by Eaton and Peterbilt for the Peterbilt Model 320 refuse truck. Eaton's HLA system is a parallel hybrid drive with a hydraulic pump/motor coupled mechanically with the engine in a post-transmission configuration. The motor/pump unit boosts the drive torque during acceleration and recuperates the energy during braking. The energy storage is provided by a pressure accumulator with the energy capacity of approximately 380 kJ. Eaton estimates that the HLA system can achieve a 25 to 35 percent improvement in energy efficiency, a corresponding level of emission reduction, and a 50 percent reduction in brake wear for a vehicle operating on a stop-an-go cycle. In its present form, the system adds about 400 pounds (180 kg) to the truck curb weight [17].

Dana

Dana is involved in a demonstration project to develop a hydraulic hybrid system for a Mack LE613 refuse truck. Dana's powertrain uses a hydraulic torque assist system developed by Permo-Drive Technologies. Permo-Drive is an Australian company that developed a hydraulic Regenerative Drive System (RDS) for heavy vehicle transportation. The system uses high-pressure piston accumulators to recapture kinetic energy normally lost during braking through a motor/pump integrated to the driveline. The RDS is said to achieve fuel economy up to 38 percent while delivering additional power. Current applications of this system are primarily military vehicles [18,19].

The U.S. Environmental Protection Agency

The EPA has been the main driving force in U.S. hydraulic hybrid research and has developed and patented a hydraulic hybrid drive system. The EPA is currently involved in a natural gas hydraulic hybrid refuse truck demonstration project based on the Autocar Xpeditor platform. Parker Hannifin is the supplier of hydraulic components and systems. The project is supported by Waste Management, a part of the largest refuse collection business in the U.S. [20].

Fiba Canning

Fiba Canning is an Ontario company that supplies and repairs cryogenic trailers, tube trailers and customer stations; provides trailer manufacture and repairs; and performs research and development in alternative fuel vehicles. In the mid-1990s, the company developed the Cumulo System, which consists of a hydrostatic transmission with energy storage capacity. It has been installed into a prototype front loader refuse truck. The system demonstrated energy consumption reduction by 50 percent [21]. Fiba Canning and its partner Volvo Flygmotor designed, built, demonstrated and evaluated the performance of a CNG-powered refuse collection vehicle. It was equipped with brake energy storage, a recovery propulsion system, and dual steering axles. However, the technology has not yet been commercialized. Parker Hydraulic is the current owner of the technology, having acquired the hydraulic division of Volvo.

3. DUTY CYCLE

3.1 Duty Cycle Characteristics

Residential refuse collection is the primary target for hybrid truck application because of its extremely frequent stopping and very low speeds. In general, the residential duty cycle of a refuse trucks consists of the following tasks:

- driving from the depot to the route
- collecting refuse on a residential area route
- driving from the route to the landfill to transfer the load
- returning from the landfill to the route

Typically, the truck has to complete more than one cycle per daily shift, as its load capacity is reached in three to four hours of operation.

A daily breakdown of refuse truck operations is shown in Figure 1.

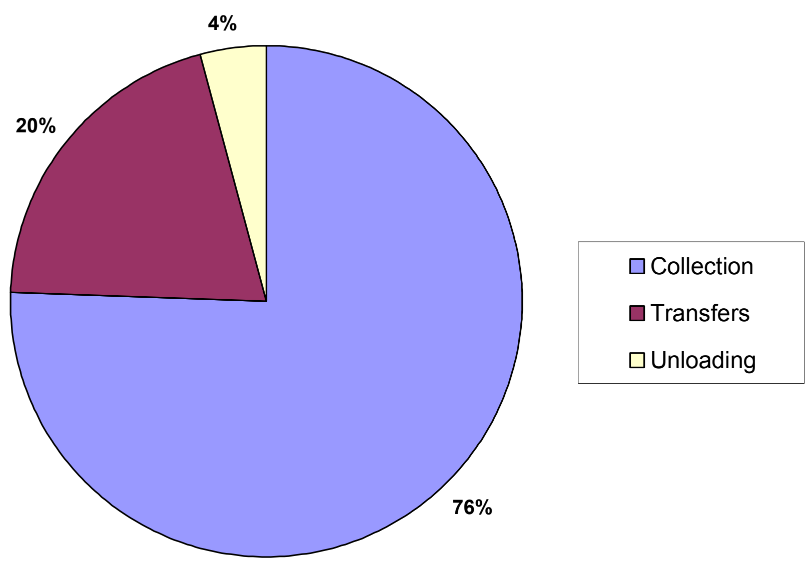

Figure 1: Daily Breakdown of Refuse Truck Operation

As seen in Figure 1, 76 percent of daily operating time is spent collecting refuse and only 20 percent of the time is spent in normal traffic conditions getting to and from the depot to the collection route and to the landfill. The remainder of the time is taken by truck unloading. Operator breaks are not counted, as it is assumed that the vehicle's engine is off. The data clearly identify two distinct operating modes of the refuse truck – a "collection" mode on the collection route and a "transfer" mode that represents a mix of urban and highway driving similar to other truck applications in this weight class.

A conventional powertrain is relatively efficient in the transfer mode and the benefits of a hybrid system, although possible, may not be sufficient to justify its implementation solely for this mode. The collection mode, however, imposes very inefficient operating conditions on the engine, resulting in a significant potential for energy efficiency improvement and emissions reduction through hybridization.

The collection mode is the focus of this study, as this is where the truck operates most of the time. The collection mode is a series of micro-cycles, each representing the truck moving from one collection point to the next, followed by refuse loading and compacting. The duration of each micro-cycle and the resulting frequency of stops depends on the geographic features of the serviced area. Typically, the trucks make over 100 stops per hour, making this mode one of the most demanding duty cycles experienced by commercial vehicles.

Figures 2 and 3 present examples of collection and transit modes for a fully loaded 25,500 kg (56,000 lb.) GVW truck with a side loader.

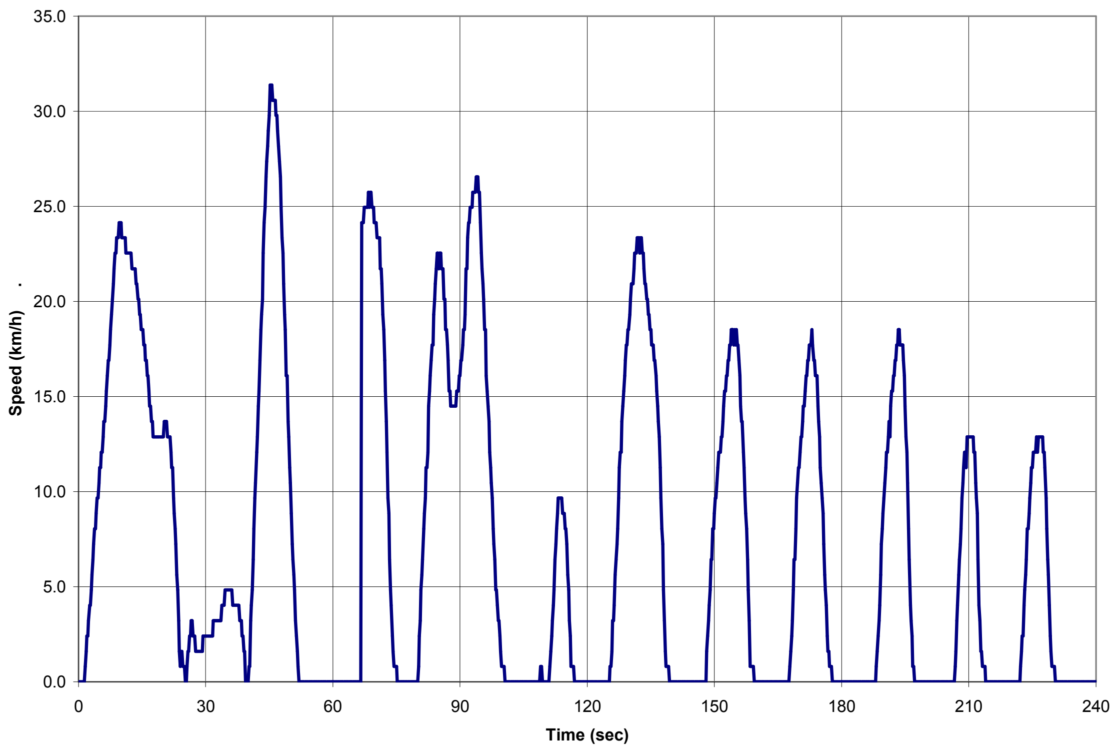

Figure 2: Collection Mode Example – Vehicle Speed Profile

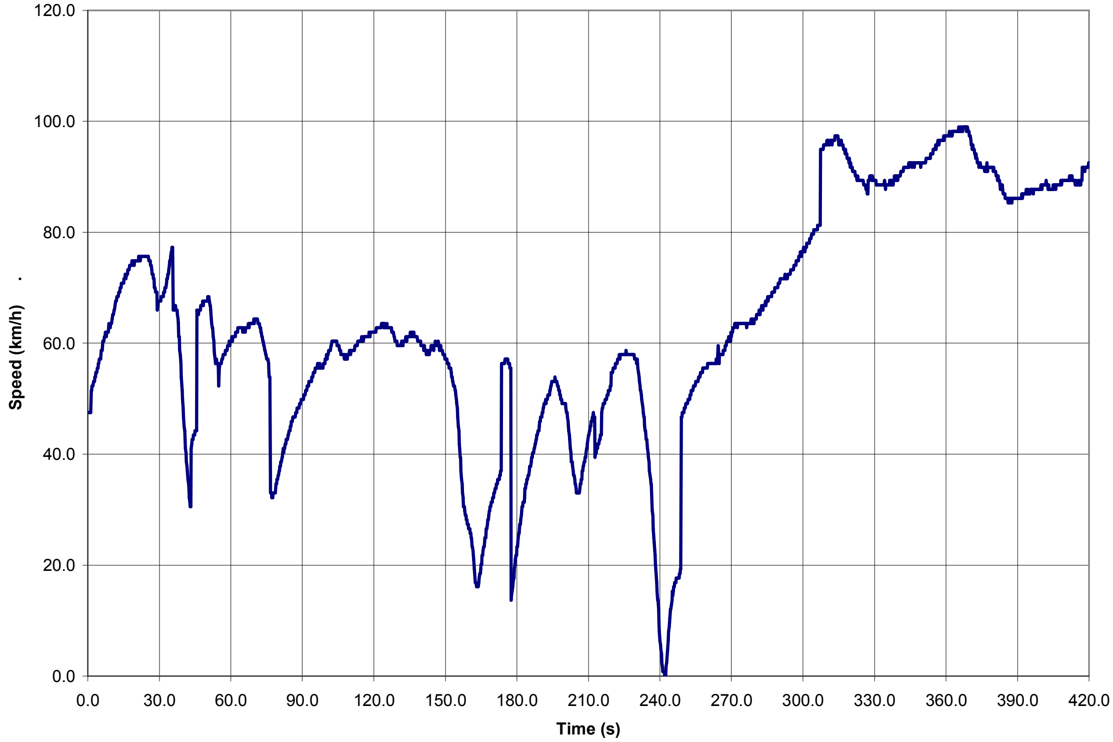

Figure 3: Transfer Mode Example – Vehicle Speed Profile

3.2 Traction Power Requirements

The traction power needed to negotiate a given duty cycle is determined by the vehicle speed profile, route elevation profile (road grade) and vehicle weight.

Vehicle Speed Profile

The duty cycle speed profile used in this study was based on operating data collected in 2003 in Saint-Nicolas, Quebec, by Équipement Labrie. The available amount of data was not sufficient to perform a meaningful statistical analysis of the duty cycle. In order to relate the data collected in Saint-Nicolas to other operating environments, the principal parameters of the Saint-Nicolas collection mode data were compared to the New York City Garbage Truck cycle [4] and the duty cycle profile described by ARC [5].

The analysis of the duty cycle data reveals the following observations:

- Maximum speed achieved on a micro-cycle typically does not exceed 25 km/h. For comparison, the New York Garbage Truck cycle [4] contains six cycles at 8 km/h (5 mph), two cycles at 20 km/h (12.5 mph), and one cycle at 32 km/h (20 mph). A sample typical micro-cycle presented by ARC [5] has a maximum speed of 23 km/h.

- The duration of a micro-cycle on the Saint-Nicolas route ranges from 4 to 24 seconds. The majority of the micro-cycles are under 10 seconds. On the NYC Garbage Truck cycle, the micro-cycles are substantially longer – 5 mph micro-cycles are 16 seconds in duration, 12.5 mph micro-cycles are approximately 25 seconds in duration and the 20 mph micro-cycle lasts 40 seconds. The duration of a micro-cycle reported by ARC is 16 seconds.

- The loading time for the truck on the Saint-Nicolas route is very short – typically 6 to 8 seconds. This is substantially faster than for the NYC Garbage Truck cycle, which assumes a loading time of 30 seconds and an additional 30 seconds for packing every third stop. This is likely due to the much more efficient automatic side loading used in the Labrie truck. The NYC Garbage Truck cycle was developed for an older truck with manual loading.

- The acceleration profile is similar for all cycles – average time to reach 20 km/h is 5 seconds for the Saint-Nicolas and ARC cycles. The New York Garbage Truck cycle assumes 6 seconds. Analysis of the acceleration profiles in the Saint-Nicolas data shows that the acceleration time to 20 km/h can be as short as 4 seconds.

- The number of stops per hour for the Saint-Nicolas cycle is 144. An equivalent stopping frequency for the NYC Garbage Truck cycle would be 90 stops per hour. The Ricardo study [6] reports a total number of stops of 459 over an 8.42 hour working shift. This translates into an average of 54 stops per hour. However, the actual stopping frequency is likely to be in the order of 70 to 80 if the transfer times are accounted for.

- The micro-cycle profile for the Saint-Nicolas data does not change significantly with the payload. This seems inconsistent with the refuse truck application, where the weight of the vehicle changes gradually over the course of the cycle. The changing mass affects the performance of the vehicle, so the acceleration rate at the beginning of the cycle should be higher than at the end of the cycle. However, it has been found that the actual speed profile is only slightly faster at low loads compared to that at full load. It may be due to the technical limitations imposed by the engine control system, but it is also likely that the speed profile reflects a "natural'" behaviour of the driver, who estimates the vehicle acceleration rate required to drive between two collection points in a smooth manner without an excessive use of brakes.

In conclusion, the Saint-Nicolas data represent a typical micro-cycle profile for modern refuse trucks with side loading capability. ARC data collected for a similar vehicle platform conform well with the Saint-Nicolas data. The NYC Garbage Truck duty cycle is less aggressive and seems to represent an older technology. Its kinematic parameters are somewhat lower than those of the Saint-Nicolas and ARC cycles, indicating a lower power vehicle. The NYC Garbage Truck cycle loading times are much longer, resulting in a stopping frequency almost 40 percent lower.

A duty cycle based on the full load performance is a practical approach for the purpose of comparative energy use simulation, and so it has been assumed in this study. It should be noted that for detailed energy use analysis or energy management system development, a complete cycle covering the entire period of vehicle filling may be needed.

Road Grade

The road grade data were not available for the given route. For the purpose of a comparative study, it is reasonable to assume level road. Previous experience in simulation of urban vehicles indicated that the road grade profile does not significantly affect the energy consumption of a vehicle in typical urban conditions.

It should be noted that vehicles optimised for certain geographic areas with frequent steep route sections should include the grade data as a design variable.

Payload

The refuse truck payload increases gradually over the course of the cycle until the vehicle reaches its maximum weight (GVW). The operating data indicate a pick-up frequency of up to 144 collections per hour. Based on the average single load mass of 21.8 kg, the vehicle collects 3139 kg per hour. At this rate, the maximum payload of 11,200 kg is reached in approximately 3.5 hours. Depending on local regulations, the vehicle may complete up to two cycles in a single day. It is likely that the second collection cycle will be shorter and the vehicle may not be loaded to full capacity at the end of the shift.

3.3 Hydraulic System Power

The hydraulic system of the refuse truck is supplied by a variable displacement pump driven directly from the engine. A sample pump power profile on a section of a collection route is shown in Figure 4.

From Figure 4, it can be seen that the pump operates at minimum power between 8 and 12 kW to sustain the system's pressure. During each pick up, two stages can be identified. The pick up begins 2 to 3 seconds before the vehicle stops and lasts approximately 7 seconds with the peak power of up to 25 kW. Following the initial stage, the power reaches a peak of approximately 42 kW for another 5 seconds.

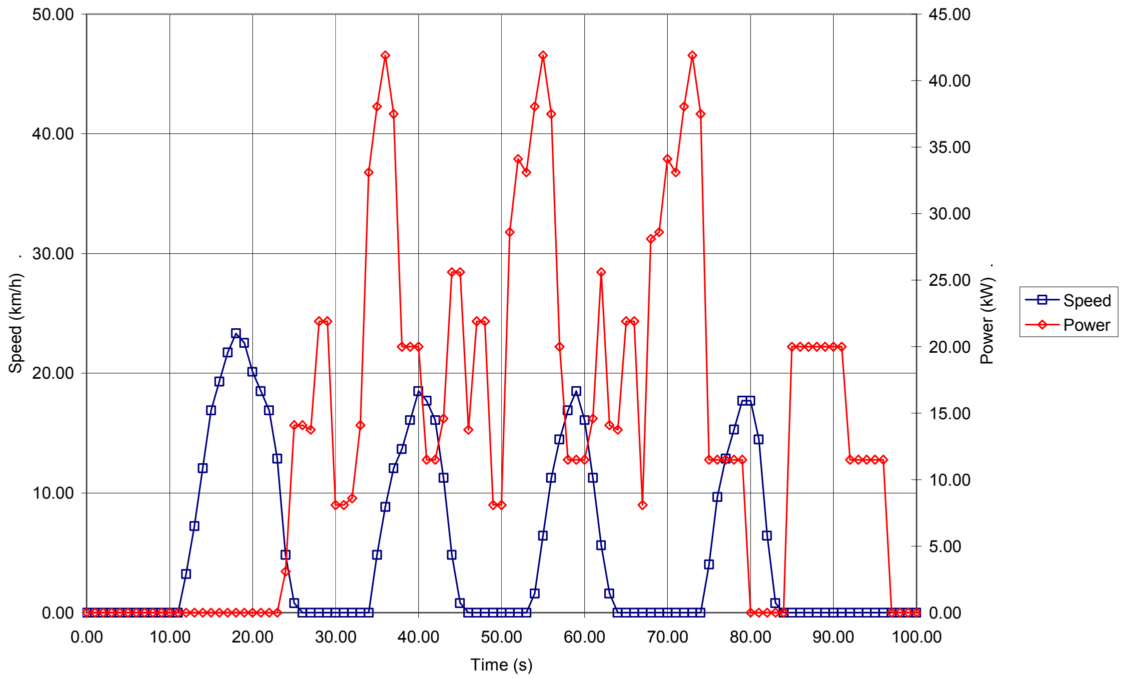

Figure 4: Hydraulic Power Demand on Saint-Nicolas Route

4. HYBRID POWERTRAIN CONCEPTS FOR REFUSE TRUCK

From the standpoint of system architecture, it makes no difference whether the system under consideration is electric or hydraulic. The mechanical arrangement of components is the same for each configuration. Similarly, the energy flow patterns are similar, with hydraulic fluid flow and pressure described with similar mathematical models as electric current and voltage. The differences between the two technologies lie in specific design details such as gearing and control approach dictated by different component characteristics.

4.1 Electric Hybrid Drive Technology

The electric hybrid systems for light and heavy duty vehicles have been in development for more than two decades and the number of hybrid vehicles on the market is growing rapidly. In the case of heavy duty drives, the power system integration issues are generally well understood, but the cost and availability of components still remains the limiting factor. Although motors and batteries are widely used in various industries, the stationary applications never required the level of weight and efficiency optimization needed for automotive powertrains. Early electric hybrid prototypes, built using industrial components, could not achieve the performance and efficiency needed to compete with conventional drives. Large high-efficiency electric machines and electric energy storage solutions are still new technologies and have not yet benefited from economy of scale. However, the field is growing rapidly with new products being introduced to the market and it is likely that the cost and quality of electric system components will improve significantly in the near future. The light duty automotive industry is driving the innovation and the light duty technology is transferred to heavy duty applications.

The characteristics of electric motors are very suitable for traction as they provide the maximum torque at very low speeds. The torque profile is practically flat until the motor reaches its maximum power, resulting in a good acceleration profile. The maximum efficiency of electric motors is in the order of 93 to 95 percent for permanent magnet machines and 92 to 93 percent for induction motors, not including the loss in the motor controller. The efficiency drops to 80 to 85 percent at low speeds and low loads, and the shape of the motor efficiency map depends on the specific motor design. Overall, the permanent magnet motors are more compact and have a slight efficiency advantage over induction machines, but at a significant cost premium. The size and efficiency of an electric motor is a function of its speed, and traction motors are typically high-speed machines, with a maximum speed of up to 12,000 rpm. The motors have to be geared to reduce the speed and increase the torque as well as allow the motor to operate in the best efficiency range.

Traditionally, the weakest part of electric drives has been energy storage. The main challenges are energy density, cost and durability of energy storage. Available electrochemical battery technologies include advanced lead-acid, nickel-metal hydride, nickel-sodium sulfate (Zebra) and lithium-based (Li-Ion, Li-polymer) batteries. Lead acid, Ni-MH and Zebra battery packs are available commercially for heavy duty applications. Lithium-based batteries are still not generally available for traction application, although several low-volume systems have been demonstrated. For practical hybrid drive application, Ni-MH batteries represent the best compromise between energy density and cost. However, all existing battery technologies suffer from poor durability. Typically, the life of an electrochemical battery is only up to 1000 deep discharge cycles. At the partial discharge levels typical for hybrid drives, the batteries can achieve a lifetime of up to 200,000 cycles. Considering that a refuse truck can require up to 1200 partial discharge cycles per day, electrochemical batteries may not be a viable energy storage option for such a system as they would have to be replaced as often as every two years. High power requirements would also require relatively heavy and bulky battery packs. An alternative to an electrochemical battery is an ultracapacitor. Ultracapacitors do not rely on chemical processes to store electrical energy, so the durability of the device is not a function of its depth of discharge. The deep discharge lifetime is typically 500,000 cycles and at lower discharge rates, the durability of the ultracapacitor pack may be comparable to the other components of the system. Ultracapacitors have a very high power density but low energy density compared to batteries. In a hybrid refuse truck system, the energy requirements are relatively low and ultracapacitors may be a practical option. The major limitation is still cost, but the price of ultracapacitors is dropping rapidly and the technology is approaching a point where it is becoming competitive with batteries, particularly in high power applications such as refuse trucks.

A major advantage of the electric system is its flexibility, both in terms of mechanical integration as well as the system control. Modern power electronics make it possible to have a very efficient voltage and current control to maximize the efficiency of the system. The selection of system voltage is a trade-off between the cost of power electronics and the cost of the electrical components. At higher system voltages, the current levels are lower resulting in smaller and less expensive electrical components. The power electronics cost increases with system voltage. Typically, a 300 V power system can support an electric drive up to 100 kW peak output. At higher power levels, a 600 V or higher voltage is necessary to reduce the maximum currents to 250 to 300 A.

4.2 Hydraulic Drive Technology

Hydraulic components have been in mass production for decades and are used extensively in traction systems for off-road and industrial vehicles. Hydraulic motors and pumps are mature products, and major improvement in the technology and significant cost reduction is less likely than for electric components. The maturity of hydraulic components is currently an advantage of this technology over the electric components, although the balance may change in the future. In the case of a refuse truck, the hydraulic approach also has an advantage in that the vehicle is already equipped with a hydraulic system for refuse handling.

4.3 Hybrid Powertrain Architecture

The general classification of hybrid drives is based on the way the engine power is transferred to the wheels. In a series system, the engine power is converted into electricity (or hydraulic pressure) to drive the traction motor without any mechanical coupling between the engine and the wheels. In a parallel system, the engine is mechanically coupled with the wheels so that the wheel torque and speed are proportional to the engine torque and speed. In a series-parallel system, the engine power is split into a mechanical and an electric path so that the engine speed and torque are decoupled from the wheels as in the series system, but a significant share of the engine torque is directly transferred to the wheels through a mechanical connection as in a parallel system.

Two unique features of the refuse truck application are the two distinct operating modes and a significant power demand for the hydraulic equipment that loads and compacts the collected refuse. Due to the need for extended operation at highway speeds, a pure series system is not practical for refuse trucks. The large size and poor aerodynamics of the vehicle require a large engine to maintain highway speed. However, series hybrid systems are viable in the collection mode. A dual-mode system, operating as a series hybrid in the collection mode and a conventional powertrain (or a parallel hybrid) in the transfer mode would eliminate the main disadvantage of the series system – poor efficiency at highway speeds. Parallel and series-parallel architectures are also possible for refuse trucks and can be implemented in various configurations.

In this section, various options of hybrid powertrain architecture are discussed. The accompanying figures use the following acronyms for component names:

AMT – automatic manual transmission
ATX – automatic transmission (with torque converter)
BAT – battery pack
ENG – engine
GEN – electric generator
GB – gear box
HM – hydraulic motor
HP –hydraulic pump
IMG – integrated motor-generator
MG – electric motor-generator
MOT – electric motor
PG – planetary gear
PA – pressure accumulator
UC – ultracapacitor pack

Parallel Architecture – Torque Assist

In a parallel system, the electric or hydraulic motor is mechanically coupled with the transmission shaft. The parallel architecture can be implemented in pre- or post-transmission configuration. In a post-transmission system, the motor is coupled with the output shaft of the transmission, while in the pre-transmission system, the motor is coupled with the input shaft between the transmission and the engine. The pre-transmission system can be integrated as a module between the engine and transmission and is sometimes referred to as Integrated Motor Assist (IMA) or Integrated Starter Generator (ISG). Hydraulic parallel architecture is sometimes referred to as a Hydraulic Launch Assist (HLA) system.

The primary function of the motor in a parallel system is to reduce the load torque on the engine during acceleration and regenerate the energy during braking. In the simplest system, the braking energy is stored in the energy storage device and returned to the motor during acceleration. However, the recovered energy represents only 25 to 50 percent of the drive energy, so the motor assist during acceleration must be limited either in duration of the pulse or by reduction of the motor torque. The motor can be also used to generate energy at lower engine loads (e.g., during constant speed driving sections); however, the viability of such an option is constrained by the duty cycle characteristics

Schematic representations of different parallel hybrid drive architectures are shown in Figures 5 to7.

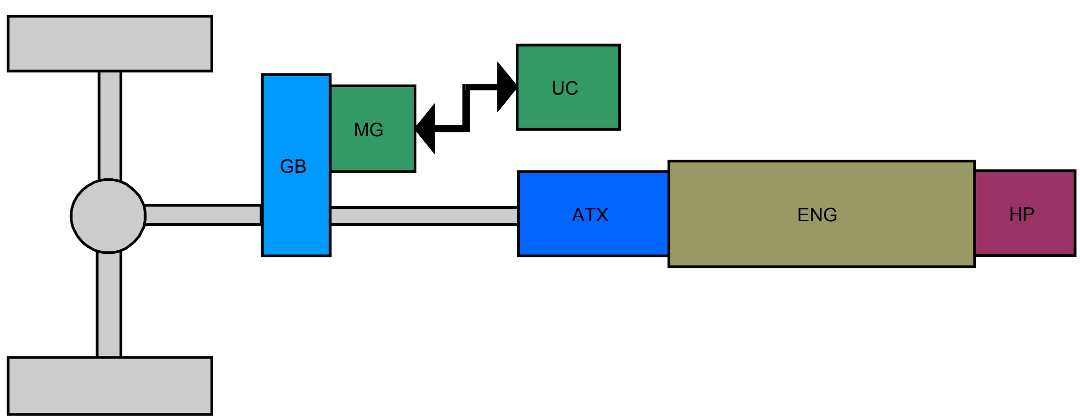

Figure 5: Electric Parallel Architecture – Post-Transmission Configuration

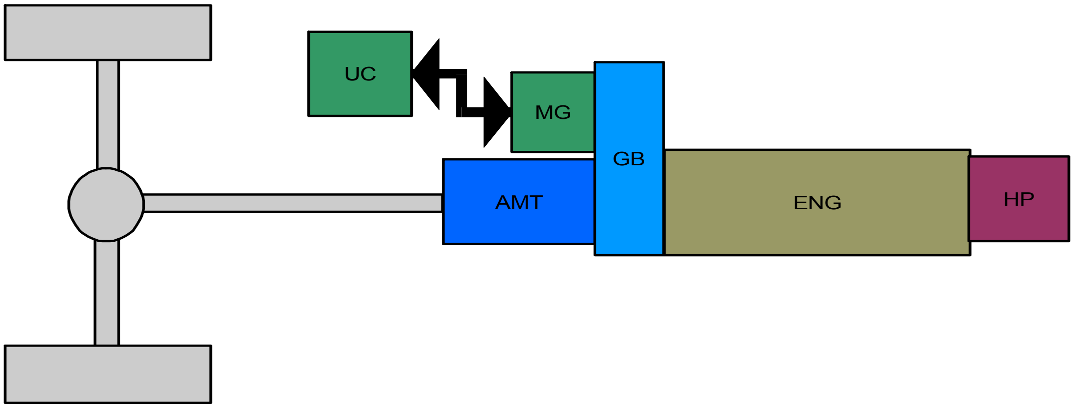

Figure 6: Electric Parallel Architecture – Pre-Transmission Configuration

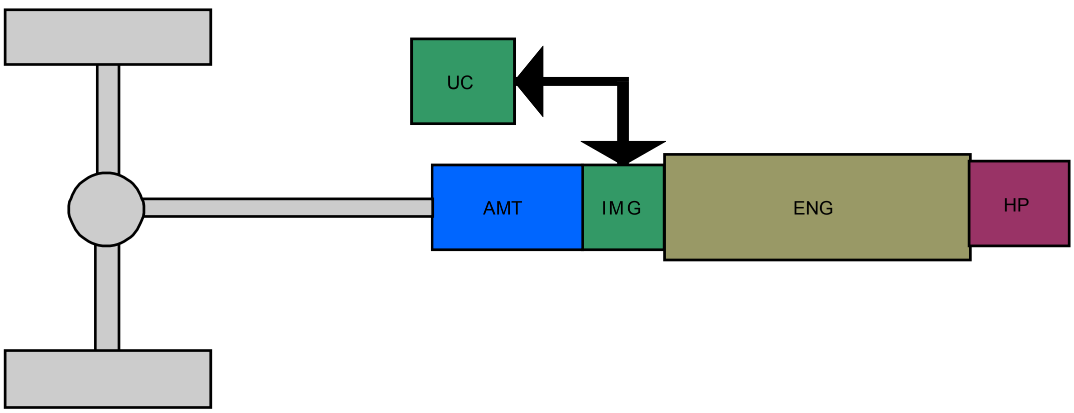

Figure 7: Electric Parallel Architecture – Integrated Motor Assist

The post-transmission parallel architecture is easier to implement as there are no modifications to the engine and transmission. The motor is geared using a single speed reduction gearbox. Single speed gear ratio requires the motor to operate in a wide speed range, reducing its overall efficiency compared to a multi-speed transmission. The motor may also require a clutch to avoid drag at highway speeds when the torque assist is not required.

The pre-transmission configuration requires substantial modifications to the conventional powertrain. The modifications include a mechanical interface between the engine and the transmission, and possibly an engine/transmission control system. Typically, operating motor speeds are much higher than those of the engine and an additional reduction gear is required. The gear ratio is lower than for the post-transmission configuration since the motor uses transmission gears. Since at higher speeds the vehicle operates at higher gears, the motor does not operate in as high a speed range as in the post-transmission configuration and the over-speed clutch is not necessary.

For the refuse truck operating in collection mode, there is little difference between the pre- and post-transmission configurations from the standpoint of motor operating conditions, as the vehicle operates primarily in first gear. However, if the motor is also to provide torque assist in transfer mode, the pre-transmission system has some advantages over post-transmission architecture. One difficulty with the pre-transmission architecture is that regenerative braking has to be done through gears. The transmission downshift algorithm may need to be modified to ensure proper regeneration characteristics. For that reason, a manual or automated manual transmission is preferred.

Parallel Architecture – Pressure Assist

In a system with a hydraulic or electric motor coupled with the drive shaft, it is also possible to use the motor in retarder mode only for capturing the regenerative braking energy and not for traction. This approach has particular merits for a hydraulic system where there is no need for the additional energy conversion step.

In the pressure assist system, the pump driven by the inertia of the braking vehicle pumps the hydraulic fluid into the pressure accumulator. The recovered energy can be then used to assist the hydraulic refuse handling system. The engine supplies full torque during the acceleration but the hydraulic equipment load on the engine is lower.

The advantage of the pressure assist option is that it is not necessary to operate the hydraulic motor at low efficiency conditions during the acceleration as the energy can be used directly by the hydraulic system. The hydraulic energy is generated by the engine at low speed conditions when the engine specific fuel consumption is very high; hence, reducing the hydraulic load has a significant effect on fuel consumption.

A schematic representation of the pressure assist system is shown in Figure 8.

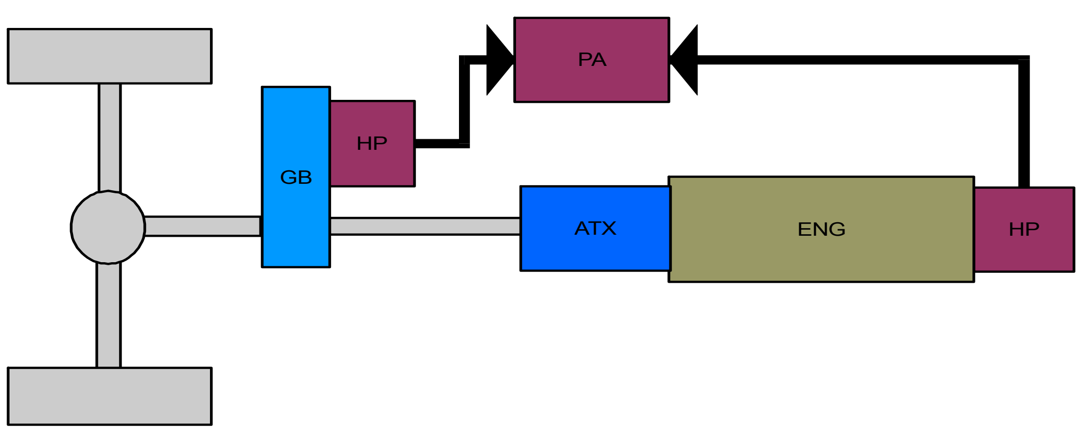

Figure 8: Hydraulic Parallel Architecture – Pressure Assist

Electric Dual-mode Architecture

A full-time series system is not practical in the refuse truck application because of the high loads in transfer mode. A dual-mode system, operating as a series hybrid in collection mode and as a parallel hybrid in transfer mode, offers the best compromise for the two distinct operating modes of the refuse truck.

The dual-mode system consists of a traction motor that can also operate as a generator (pump) for regenerative braking, coupled with the transmission via a single speed reduction gear, an energy storage device (a battery, an ultracapacitor or a hydraulic pressure accumulator), and a generator (pump) that provides the primary power to the system from the engine. As in the parallel system, the motor may be connected in post- or pre-transmission configuration.

Two possible configurations of a dual-mode system are depicted schematically in Figures 9 and 10.

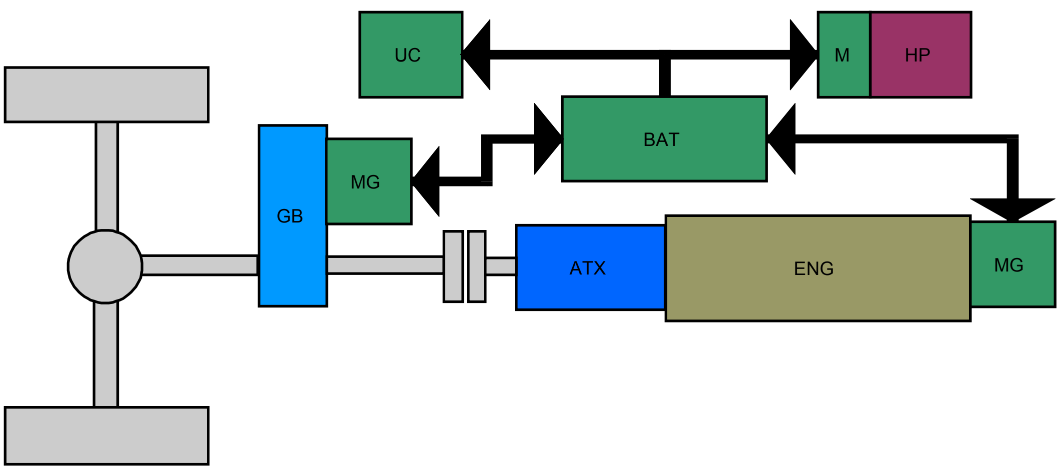

Figure 9: Electric Dual Mode Architecture – Post-Transmission Configuration

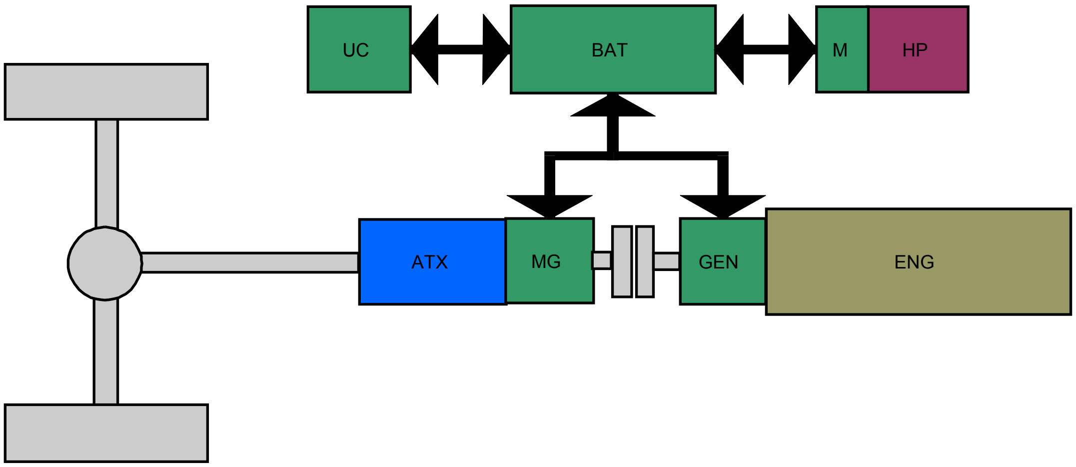

Figure 10: Electric Dual Mode Architecture – Integrated Motor/Generator/Clutch Module

The clutch separating the engine and the traction motor is used to switch between the two operating modes With the clutch open, the truck is driven by the motor and the engine operates independently, driving the generator (pump). With the clutch closed, the truck is driven by the engine, with the motors providing torque assist during acceleration and recharging the energy storage during highway driving.

In the electric dual mode system, the hydraulic pump is driven by a separate electric motor. This option offers the benefits of using a simpler, fixed displacement pump and a more effective flow control by varying the motor speed. In a general case, all auxiliary systems are driven electrically so the engine can be switched off to prevent overcharging and reduce energy loss while idling.

Electric Series-Parallel Architecture

A series-parallel hybrid architecture is the most advanced hybrid concept, from the standpoint of both mechanical complexity and control system sophistication. Although both an electric and a hydraulic version are feasible, only electric systems have been demonstrated to date.

A series-parallel hybrid system, shown schematically in Figure 11, splits the engine power into a mechanical and electrical (or hydraulic) path, depending on vehicle speed and load conditions, using two machines (motor/pump). One of the machines is coupled with the engine shaft via a planetary gearbox and acts as a generator and a constant velocity transmission. The other machine is coupled with the drive shaft and provides torque assist to the engine. An energy storage device acts as a buffer, powering the motor and accepting charge from the generator.

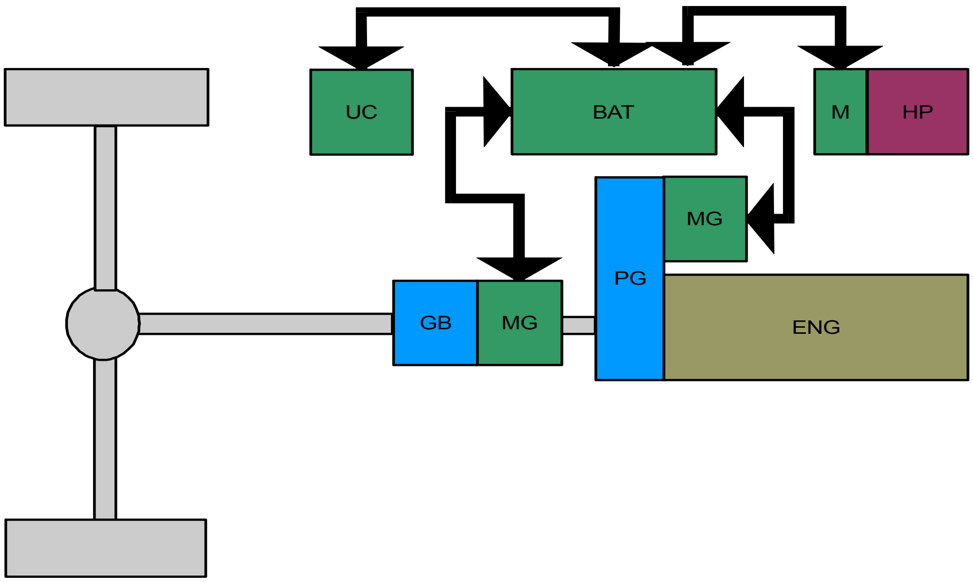

Figure 11: Electric Series-Parallel Architecture

At very low speeds, the vehicle operates in electric mode with the engine shut down, using only the battery power. In existing systems, the electric mode speed limit is between 5 and 20 km/h. Once the electric mode speed limit is exceeded, the engine is activated and a portion of the engine power is transferred through the planetary gear to the drive shaft while the remainder of the engine power is used to generate electricity that is subsequently used to power the motor. The ratio between the mechanical and electrical portion depends on the vehicle speed and the shaft load. At low speeds, the system behaves as a series hybrid, with the major share of the engine power transferred as electricity. With increased speed and load, the mechanical share of the power increases, resembling a parallel system in operation. At highway speeds, the system relies primarily on mechanical power transfer, limiting the use of the electric system to recharging the battery and an occasional acceleration boost.

The series-parallel configuration has proven to be the most effective configuration for a light duty vehicle. Integrated power split modules used in several hybrid car models are highly engineered for specific vehicle and powertrain configurations, and incorporate complex vehicle-specific control strategies. From the perspective of a low volume application, such as a refuse truck, development of a custom system is not practical. Allison's system, developed for transit buses and heavy delivery trucks, is currently the only commercially available series-parallel drive for heavy duty applications.

5. SIMULATION APPROACH

The major difficulty in evaluating the efficiency of a hybrid drive compared to a conventional powertrain is the significantly more complex pattern of energy flow in the system. The efficiency of a hybrid system is a function of not only individual component efficiencies but also the efficiency of the energy management strategy. Computer simulation is a practical tool to assess the performance and efficiency of multiple design options using a mathematical model of the system.

The objectives of performance simulation were to determine the size of the components needed to meet the design criteria, and to evaluate the dynamics of the system in typical operating conditions. The objectives of the efficiency simulation were to determine the system loads imposed by the assumed duty cycle, and calculate the corresponding energy consumption of each system component as well as the entire system.

The mathematical models used to simulate the hybrid systems were built using Matlab/Simulink® software. The structure of the simulation model was based on the "backward-calculation" principle, where the operating conditions of the system components are determined from desired duty cycle parameters. This approach is adequate for energy use analysis and does not require detailed system-specific control system modeling. The simulation model included the following elements:

- A duty cycle model used as input to define the vehicle speed and hydraulic power consumptions on the route in finite time intervals (1 second).

- The vehicle model constructed from component models connected appropriately to the specific architecture. A separate model was developed for each configuration but all models shared the common component models.

- A control strategy model appropriate for the given vehicle configuration.

The simulation process included the following tasks:

- Analyzing the torque and power requirements for the assumed design criteria (acceleration, speed, gradeability)

- Selecting the size of the principal system components and developing the conceptual models of various powertrain options (gearing selection, control strategy development)

- Verifying the system performance for given design criteria

- Simulating the duty cycle to calculate the energy consumption to estimate fuel economy and emissions

5.1 Duty Cycle Input

Duty cycle definition was based on the Équipement Labrie test data collected on a typical residential route in Saint-Nicolas, Quebec. The input variables were limited to vehicle speed and hydraulic power consumption. The road grade and vehicle mass were assumed constant for each simulation run. The constant road grade assumption was made as the route grade profile was not available and the route was in normal geographical conditions. The assumption of constant mass significantly simplifies the task of energy management modeling. The vehicle weight changes relatively slowly, and for a short cycle, it can be assumed that the energy use change between the beginning and end of the cycle is negligible. The energy consumption over the entire operating cycle is obtained by running the model with various weights and integrating the results. The additional advantage of this approach is that it clearly shows the effect of weight on energy consumption and system control parameters.

The simulation of the energy efficiency of each system was carried out using a basic 360-second cycle repeated three times for the total cycle length of 1080 seconds (18 minutes). The length of the cycle represents approximately a 1000 kg change in payload and is sufficient to establish that the system control maintains the energy balance (i.e., the energy storage device operates within assumed state-of-charge limits).

The statistical data for this cycle are shown in Table 1.

Table 1: Saint-Nicolas Duty Cycle Data

Duration	360 sec
Length	578 m
Total # of stops	15
Maximum speed	24 km/h
Average speed	5.78 km/h
Maximum hydraulic power	41 kW
Average hydraulic power	16.1 kW

The basic cycle showing the vehicle speed and the hydraulic power use profile is presented in Figures 12 and 13, respectively.

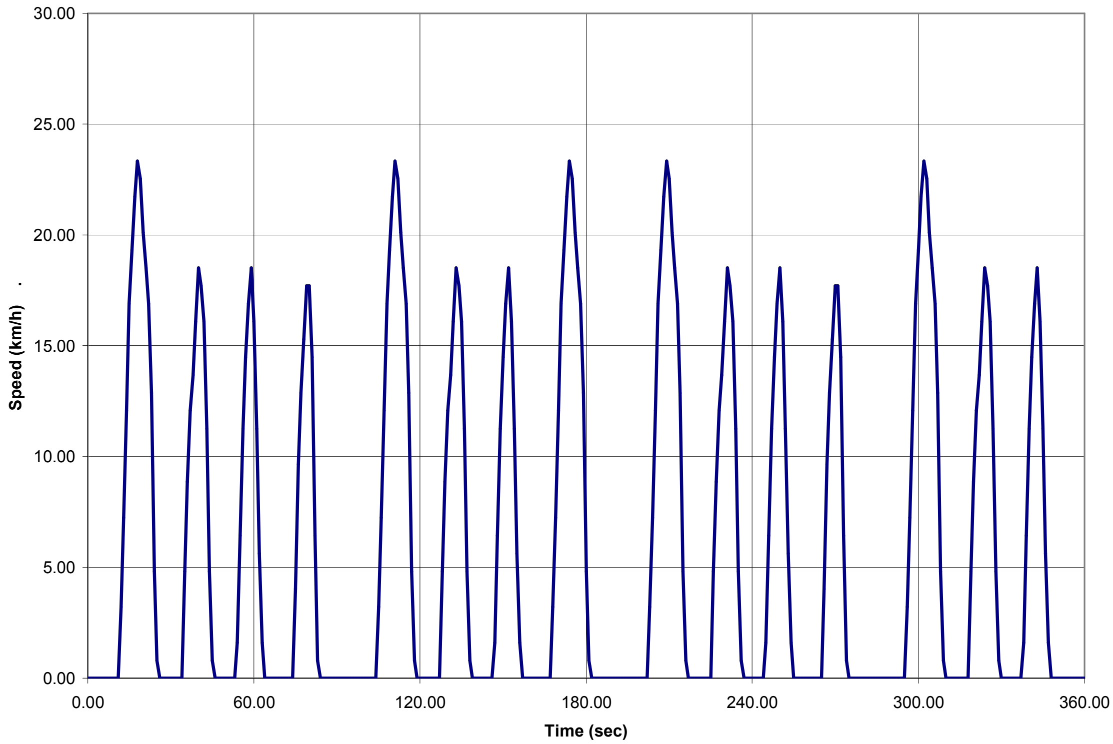

Figure 12: Simulation Input – Vehicle Speed Profile

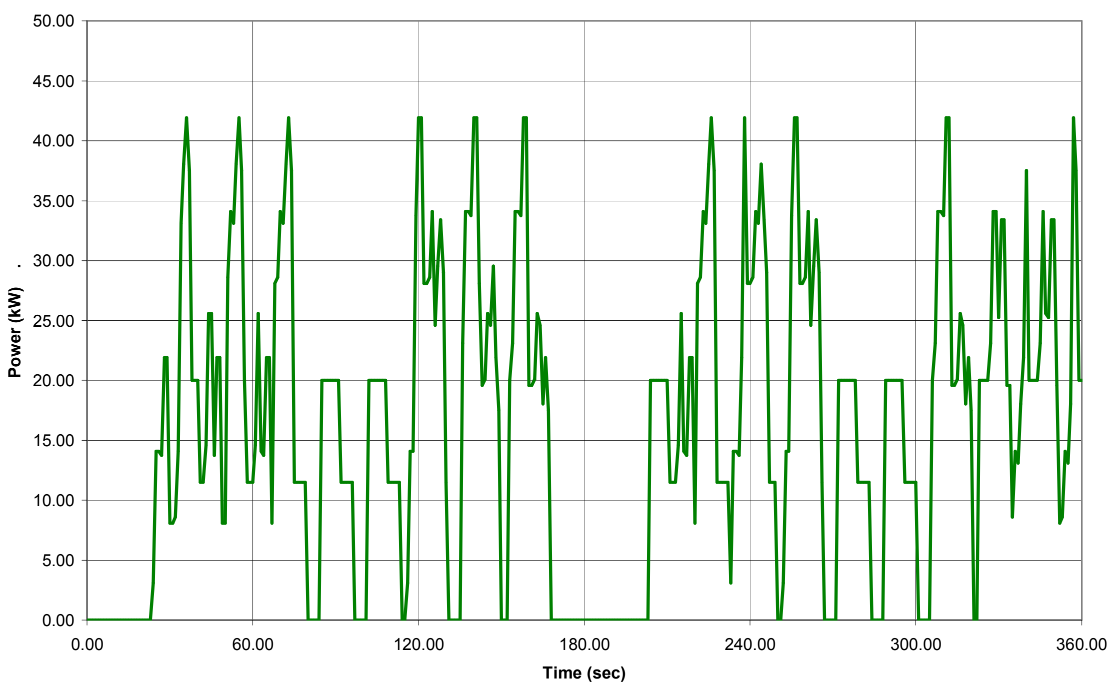

Figure 13: Simulation Input – Hydraulic Power Profile

5.2 Vehicle Model

Chassis

The baseline vehicle assumed for simulation was a 25,500 kg (56,000 lb.) side-loader truck based on the Autocar chassis. The vehicle data used for analysis are shown in Table 2.

Table 2: Baseline Vehicle Specifications

Chassis	Autocar
GVW	25,500 kg (56,000 lb.)
Curb Weight	14,000 kg (31,000 lb.)
Frontal area (150" x 98")	8.8 m^2 (13,590 sq. in.)
Aerodynamic Drag Coefficient	0.80
Engine Model	Cummins ISM
Engine Rating	235 kW(320 hp) @ 2100 rpm
Engine Torque Max	1560 Nm (1150 lb ft)
Transmission Model	Allison 4500 RDS 5 speed
Transmission Rating	373 kW (500 hp)
Transmission Input Torque Max	2102 Nm (1550 lb ft)
Transmission Gear Ratios	4.70, 2.21, 1.53, 1.00, 0.76 R 0.55
Torque Converter Stall Ratio	1.58-2.42
Rear Axle Model	Arvin Meritor RT40-145
Rear Axle Final Ratio	4.88
Tires	305/80R22.5
Tire Dynamic Radius	0.51 m (500 revs/mile)

Drive Line

The drive line model included energy losses in the rear axle and, if applicable, motor speed reduction gearing. The efficiency of a single gear set was assumed at 97 percent.

Electric Motor/Generator

The electric motor model included torque-speed characteristics and a motor efficiency map as a function of its speed and torque. The motor model calculates the net energy needed from the DC bus at desired torque and speed conditions. A generic induction motor model was used with a maximum speed of 12,000 rpm and maximum efficiency of 93 percent (including inverter). The model was based on the 120 kW (peak) motor described in [22]. The maximum torque profile was scaled to represent motors in the power range from 90 to 180 kW.

Hydraulic Motor/Pump

The hydraulic motor model included a maximum torque-speed characteristic calculated as a function of system pressure at maximum displacement. The efficiency of the pump/motor was represented by look-up tables as a function of the system pressure, shaft speed and motor displacement. The model calculated the hydraulic fluid flow required from the system to meet the desired shaft torque and speed conditions.

It was assumed that the hydraulic machine can operate as a pump or motor with the same performance and efficiency throughout most of the operating range. The only difference is at low speeds (under 500 rpm), where the pump does not generate flow but the motor does provide full torque, albeit at reduced efficiency.

The motor/pump data are based on specifications of variable displacement pumps manufactured by Sauer-Danfoss in the displacement range from 55 to 250 cm^3 per revolution [23].

Ultracapacitor

The ultracapacitor model calculates the energy losses incurred during cycling the energy to and from the device to the DC bus. For the purpose of this analysis, a simplified energetic model was used that assumes an average roundtrip efficiency. The effects of state-of-charge and voltage variation are not modeled. The efficiency of the device is assumed at 90 percent. The reported efficiency of an ultracapacitor pack varies from 70 to 95 percent, depending primarily on the depth of discharge and the number of cells in the pack [24].

Hydraulic Accumulator

The hydraulic pressure accumulator model calculates the system pressure as a function of volume of the hydraulic fluid pumped to and from the device. An adiabatic process is assumed for pressure change calculation. The system is assumed to operate at 34.5 MPa (5000 psi). The roundtrip energy efficiency of the device is assumed at 96 percent [25]. Model parameters are based on published specifications of hydraulic accumulators manufactured by Hydac [26].

Transmission

The transmission model calculates torque and speed at the transmission input shaft required to provide desired torque and speed on the transmission output shaft at given gear ratio and accounting for energy losses. A simplified model of the torque converter is used for low speed conditions where the transmission shaft speed is below the idle speed of the engine. The model data are based on published specifications for the Allison RTD 4500 5-speed automatic transmission [27].

Engine

The engine model calculates engine fuel consumption for the desired torque and speed conditions. The model includes engine torque-speed characteristics to limit the torque to the actual maximum achievable by the engine at a given speed. Fuel consumption is calculated using the Brake Specific Fuel Consumption (BSFC) map as a function of instantaneous engine speed and torque. The shape of the BSFC map is derived from generic data for a large diesel engine. The map is scaled to reflect the actual data provided by the engine manufacturer for wide open throttle conditions. The model data are based on a Cummins ISM V320 turbocharged and charge cooled 10.8 litre diesel engine [28].

Powertrain System Model

Possible hybrid powertrain configurations for a refuse truck were modeled using common component models. The components were sized for specific characteristics of each model.

The following refuse truck powertrain configurations were modeled:

- Baseline Conventional System (ICE)
- Electric Parallel System (ETA)
- Electric Series System – Dual Mode (EDM)
- Hydraulic Parallel System – Torque Assist (HTA)
- Hydraulic Parallel System – Pressure Assist (HPA)
- Hydraulic Series System – Dual Mode (HDM)

Top-level diagrams of the simulation models are shown in Appendix A.

5.3 Energy Management Model

The system control and energy management of a hybrid system is a significantly more complex and hardware-specific task, as there are multiple power sources and the energy flow must be continuously controlled in response to load conditions. Development of an optimized control strategy for each of the analysed systems was beyond the scope of this project. For the purpose of energy consumption comparison between different powertrain architectures, a simplified control approach was developed individually for each system to address specific characteristics of each system.

Parallel System

The control strategy in a parallel system is directed toward maintaining the state-of-charge of the energy storage device within pre-defined limits.

Since the energy recovered during regeneration is only 25 to 50 percent of that needed to accelerate the vehicle on a given micro-cycle, in order to maintain the charge, the motor can operate only for a fraction of the acceleration time at nominal power or for the full time at reduced power. A combination of both strategies is also possible.

In the simulation model of the electric parallel drive, the energy balance was achieved by limiting the torque available from the electric motor during acceleration. The torque limit was adjusted to maintain the average state-of-charge of the ultracapacitor at a constant level regardless of the weight of the vehicle.

In a parallel hydraulic system, the controlled variable was the hydraulic motor torque during acceleration using a similar strategy as for the electric traction motor. The torque available from the motor was adjusted to maintain the average pressure of the accumulator within allowable limits. The maximum available torque was allowed during regenerative braking. The engine torque was set to meet the desired torque level during acceleration, and during braking the engine torque was set according to the demand of the hydraulic equipment.

In the alternate option, with regenerative braking energy used to support the hydraulic equipment power demand, the hydraulic motor torque was set to zero during acceleration and to maximum available during braking. The engine supplied all traction power and the balance of power needed to power the hydraulic equipment. This was achieved by adjusting the portion of the hydraulic load of the engine to maintain the accumulator pressure within allowable limits.

Series System

In a series system, the engine is decoupled from the wheels so it can be controlled independently of instantaneous power requirements. Trials of various strategies indicated that the constant speed operation is not an appropriate strategy as the average power requirements are only in the 40 to 50 kW range, and at this load level the large diesel engine is inefficient. On-off engine control strategy is also not appropriate for this application as the hydraulic power demand is very significant and would require an oversized energy storage device. On the other hand, the frequency of stopping makes a stop-start strategy questionable as the energy consumption, emissions and reliability issues associated with such a mode of operation cannot be fully evaluated without testing a prototype. A load-following strategy, where the engine responds to the road load with a certain amount of lag, is usually considered the best strategy for a series system, as it minimizes the energy losses in the energy storage device. However, the specific requirements of the refuse truck duty may require a more elaborate approach to include hydraulic power profile at stops.

For the purpose of series system efficiency evaluation, a simplified version of load-following strategy was implemented. The diesel engine was assumed to operate continuously at idling speed and rapidly increase its output during vehicle acceleration, running at torque and speed point with lowest possible fuel consumption for the given power demand. This mode has an added advantage in that the acoustic emissions profile is similar to the conventional truck at a potentially lower noise level.

The engine output power was controlled to maintain a constant average state-of-charge of the ultracapacitor for the given vehicle weight. The electric motor was assumed to provide the full torque needed to meet the traction requirements.

The control strategy for the hydraulic series system was similar to that for the electric series system. The engine was operating at idling speed, with the exception of short pulses during the vehicle acceleration. Operating points of the engine were selected to provide the best possible efficiency at a given output level. The engine output was adjusted to maintain accumulator pressure within allowable limits.

6. PERFORMANCE SIMULATION

To be commercially acceptable, a hybrid propulsion system must meet or exceed the performance of the conventional system. The performance criteria defined for the baseline system are shown in Table 3.

Table 3: Performance Criteria for 25,500 kg Refuse Truck

Maximum speed	110 km/h
Cruising speed	100 km/h
Acceleration	0-25 km/h in 6 sec
Gradeability	88.5 km/h @ 1.59%
Startability	26.1%
EV mode range	Not required
Hybrid mode range	525 km

The objective of the vehicle performance simulation was to determine the size of hybrid vehicle components necessary for each system to achieve the above criteria.

6.1 Vehicle Speed

In order to maintain the desired speed, the powertrain must be capable of delivering the torque that exceeds the road load on the vehicle at the given speed and road incline. The torque requirements of the fully loaded baseline vehicle and the torque available from the engine at each transmission speed are shown in Figure 14.

Analysis of torque requirements for the baseline vehicle confirms that the powertrain has the capability of driving the fully loaded vehicle at 110 km/h at level road and over 100 km/h on 2.5 percent grade. In first gear the engine has sufficient torque reserve to provide startability at grades exceeding 30 percent. In fact the high first gear ratio of 4.7:1 is primarily intended for acceleration at low speeds to reduce operation with the torque converter unlocked.

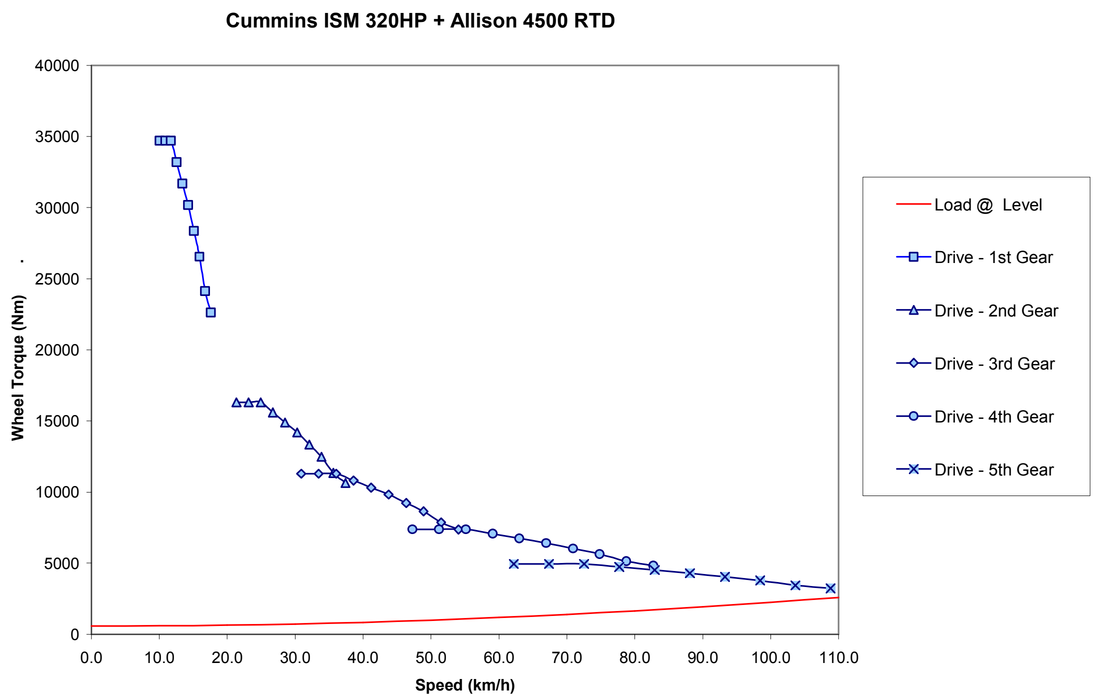

Figure 14: Comparison of Drive Torque and Road Load Torque for Baseline Vehicle

In a hybrid system, the load on the engine and transmission is lower, as the electric (or hydraulic) system absorbs a significant share of the low speed torque. The engine and transmission may be scaled down for lighter duty low speed operation, but still must provide adequate speed and gradeability in the transfer mode.

As an example, Figure 15 presents a drive torque analysis of a 5.9 litre 260 hp Cummins ISB engine mated with an Eaton 7-speed auto-shift transmission. The system provides adequate performance in the transfer mode and sufficient torque at first gear. Replacing the 10 litre ISM engine with the 5.9 litre ISB engine and lighter transmission would result in significant weight savings, offsetting most of the additional weight of hybrid components and potentially offering some cost savings to offset the cost premium of the hybrid system.

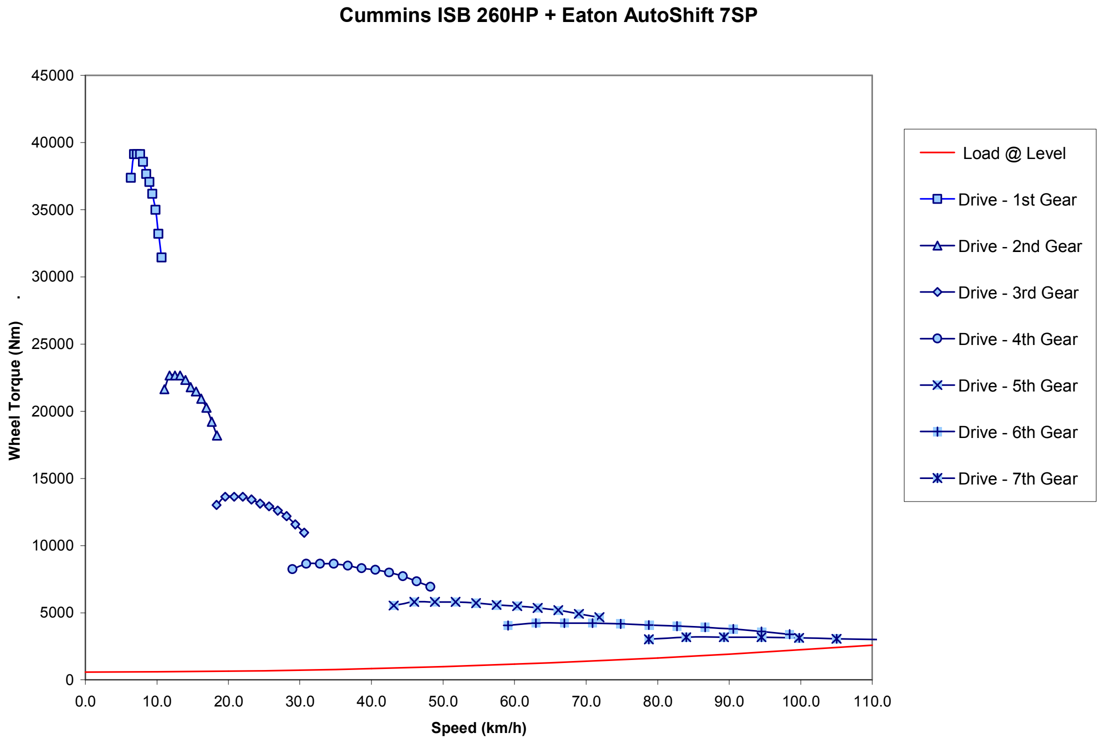

Figure 15: Comparison of Drive Torque and Road Load Torque for Baseline Vehicle with Scaled-down Engine and Transmission

The key advantage of hybrid systems is utilizing the regenerative braking energy and improving engine operating efficiency at low vehicle speed. In transfer mode, hybrid systems offer little advantage and a conventional system is the preferred option.

Series systems are not suitable for transfer mode because at sustainable high power levels, their efficiency would be lower than for a conventional system. Also, the high continuous load requirements would require the motors and their cooling systems to be oversized to handle the thermal loads.

6.2 Acceleration

Acceleration is a key criterion for refuse truck application. Analysis of the Saint-Nicolas route data and other duty cycles published in technical literature did not indicate a specific acceleration criterion. As a result, a typical micro-cycle speed profile was used to determine the power requirements at acceleration and regenerative braking. The selected micro-cycle lasts approximately 16 seconds and the truck reaches a top speed of approximately 23 km/h within 7 seconds. The acceleration time to 20 km/h is 5 seconds, which is in line with the published duty cycle data. A comparison of various micro-cycles has shown that this profile is more aggressive in terms of energy use than most of the micro-cycles that the vehicle may negotiate in its operation. Sizing the system for adequate performance on the selected event for the fully loaded system will satisfy virtually all possible conditions. This assumption is satisfactory for the purpose of this analysis, which aims to compare various hybrid architectures. In some cases, the vehicles that need to operate in heavier conditions may be equipped with more powerful drive trains, but these should be considered individually. In a majority of cases, the proposed design criterion will be adequate for typical refuse trucks similar to the baseline vehicle.

The speed profile of the selected event in collection mode used to design the hybrid system is shown in Figure 16. Corresponding torque, power and energy requirements at the wheel are shown in Figures 17, 18 and 19, respectively.

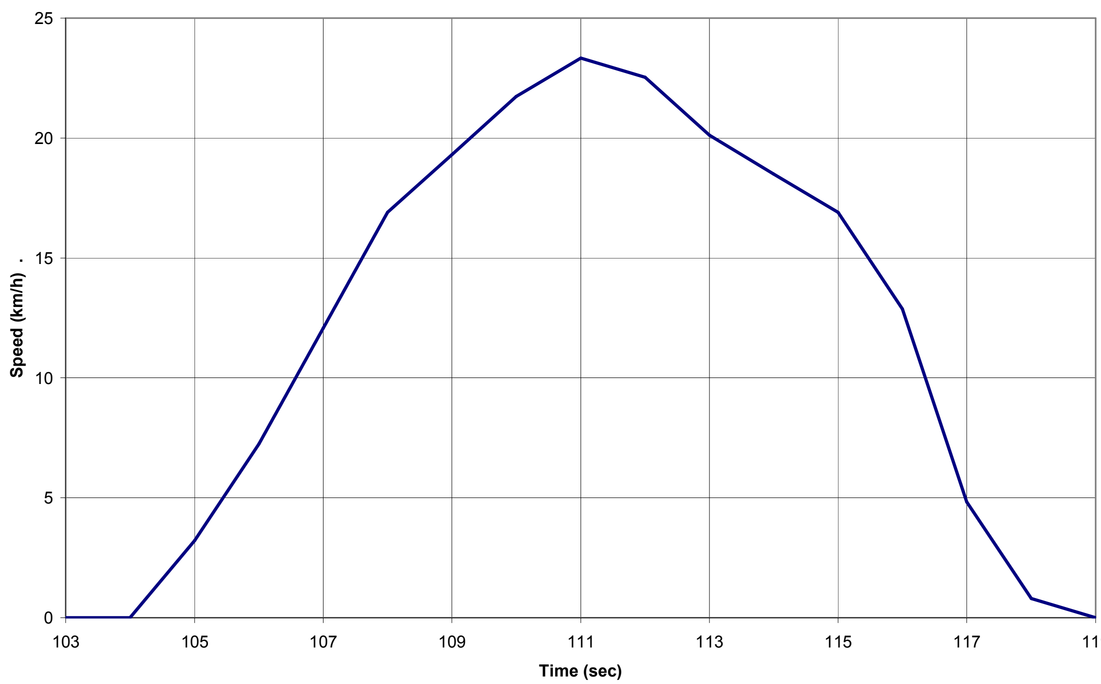

Figure 16: Design Event – Vehicle Speed Profile

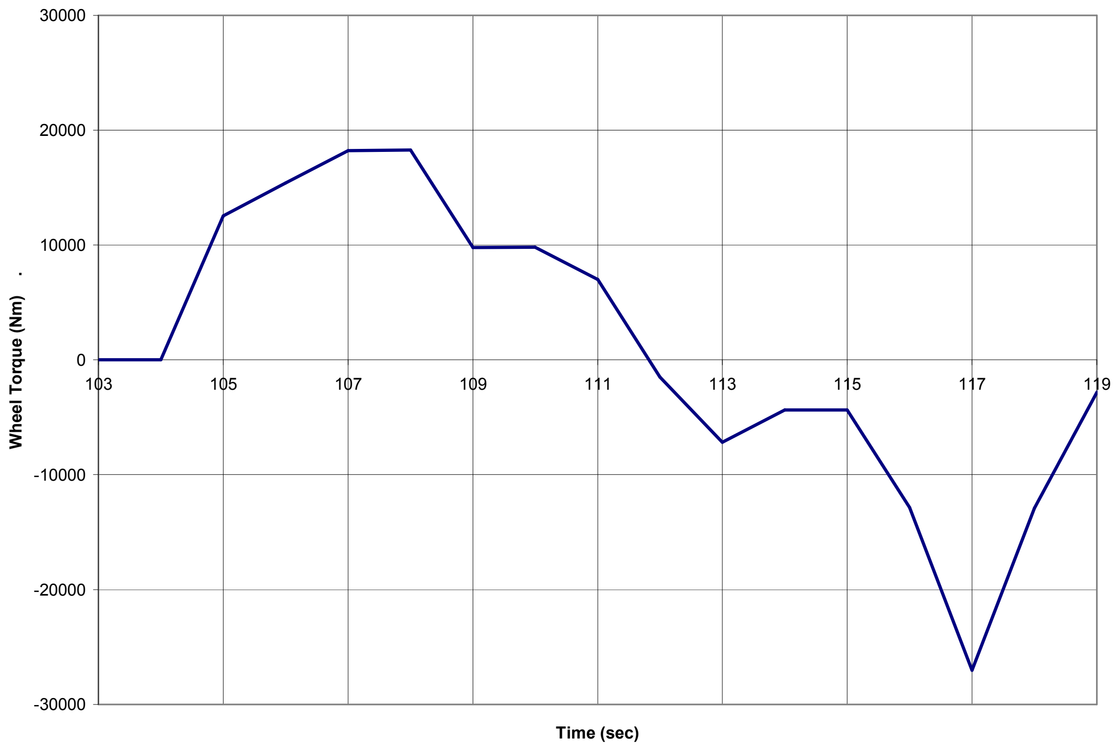

Figure 17: Design Event – Wheel Torque Profile

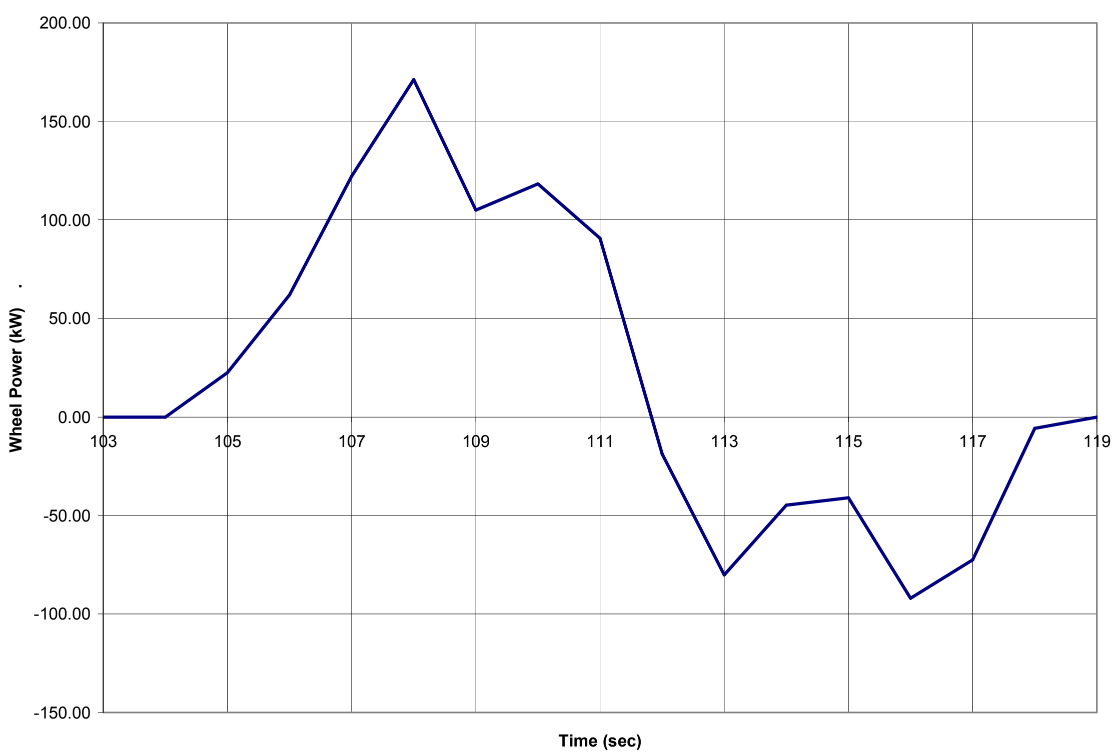

Figure 18: Design Event – Wheel Power Profile

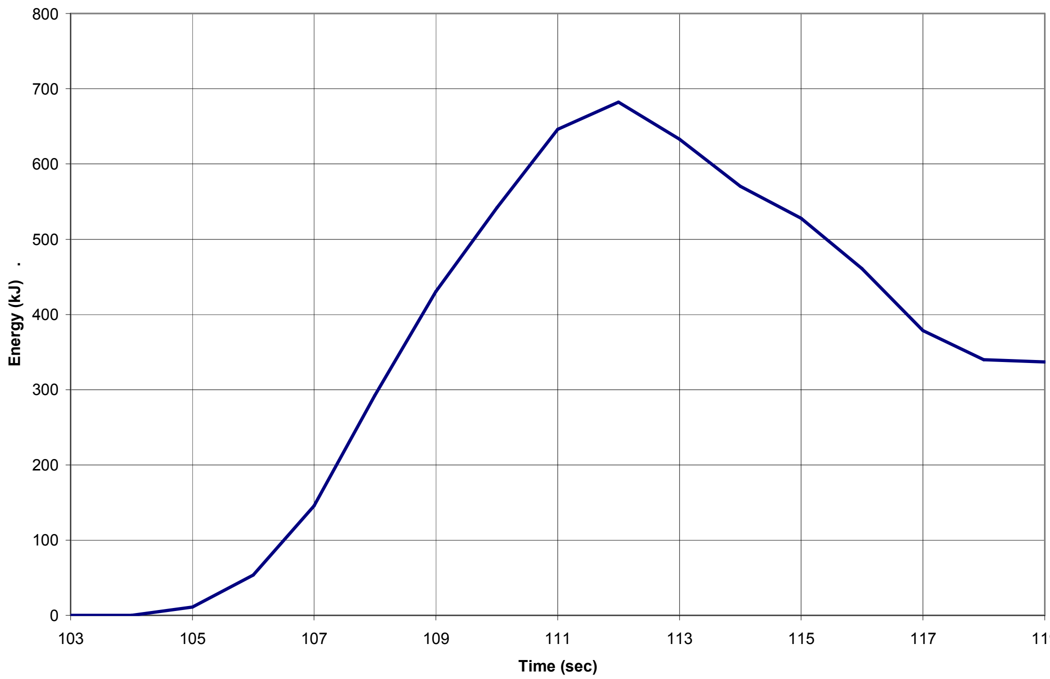

Figure 19: Design Event – Energy Use Profile

An analysis of the torque, power and energy requirements of the design event yields the following conclusions:

- The maximum wheel power demand during acceleration is 170 kW. This power level is needed only for about a half a second, and it is possible that by a slight change of the acceleration curve, the peak power can be reduced to 140 to 150 kW. This power level is required for motors in series hybrid configuration that must provide full traction power.

- The maximum wheel power during deceleration is 95 kW. Similarly, it can be somewhat reduced by changing the speed profile. This power level is required for motors in parallel configurations to take maximum advantage of the regenerative braking energy.

- The energy needed to accelerate the vehicle to 23 km/h is 680 Wh, but with full recuperation of braking energy, the total energy needed to negotiate the event is 340 Wh. This indicates that the potential for energy recovery is a maximum of 50 percent. Theoretically an energy source that is capable of providing 340 Wh of energy would satisfy the traction energy needs of the event. However, after accounting for energy losses in the driveline, motors and the energy storage itself, the minimum energy capacity of the energy storage device should be in the order of 500 Wh.

Apart from the power and energy requirements of the motors and energy storage devices, it is necessary to evaluate their torque-speed characteristics from the standpoint of their compatibility with the load profile. In series systems, the motor must provide sufficient torque to meet the entire road load at any time during the cycle. In parallel systems, the acceleration analysis is not critical, as the engine is always capable of providing the required torque. The motor assist can be used to reduce the load on the engine, maintaining the same acceleration to reduce fuel consumption. Alternatively, the motor can be used to improve the acceleration of the vehicle while maintaining the fuel consumption and emissions of a conventional vehicle. The latter approach, although possible, defeats the purpose of the reducing the fuel consumption and emissions of the vehicle and is not considered in this study.

Conventional Powertrain

Figure 20 presents a comparison of baseline conventional drive line torque and the load torque as a function of vehicle speed during acceleration. It is apparent that the engine has satisfactory torque to meet the vehicle demand, but it reaches its maximum speed at only 18 km/h so the shift to the second gear is needed to get to the peak speed of the design event.

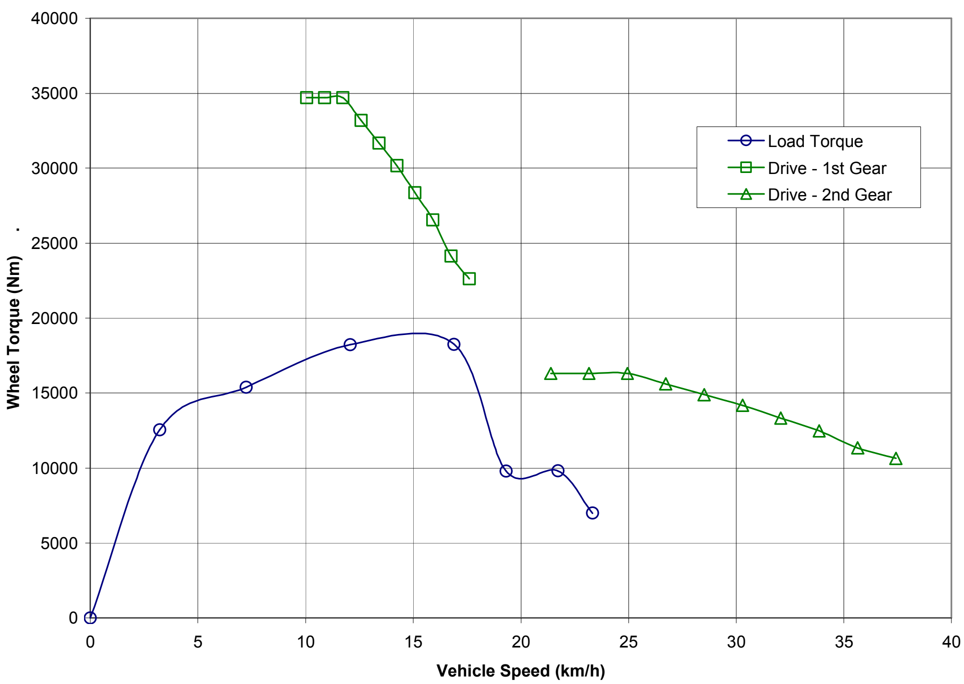

Figure 20: Load Torque versus Drive Torque – Conventional Powertrain

Electric Powertrain

Figure 21 presents the drive torque of a 150 kW induction motor (12,000 rpm maximum speed) geared to meet the load torque requirements. The gear ratio is 14.1:1, which represents the overall reduction ratio if the motor is in the post-transmission configuration or a combination of the transmission first gear ratio (4.7:1) and the motor reduction ratio (3:1) in pre-transmission configuration. Although the peak torque of the electric motor is lower than the baseline engine, the torque profile results in performance similar to the conventional vehicle.

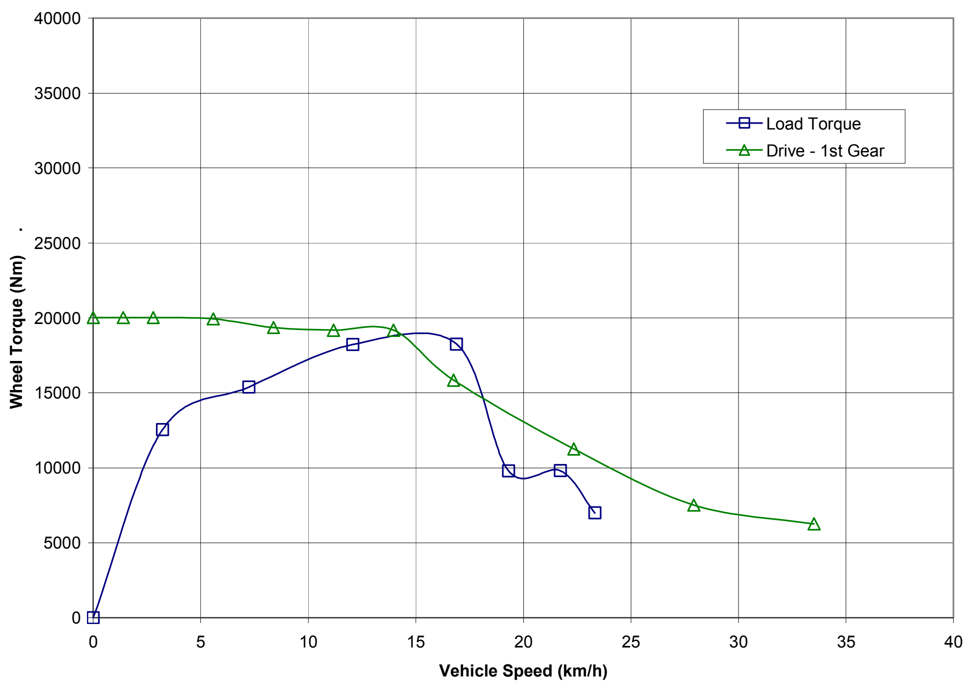

Figure 21: Load Torque versus Drive Torque – Electric Powertrain

Figure 22 compares a simulated acceleration profile for a 150 kW electric drive with the acceleration profile of the design event for fully loaded truck. The electric drive is capable of accelerating the vehicle to 20 km/h faster than a conventional vehicle, within 4 seconds that represents the most aggressive acceleration curve observed on the Saint-Nicolas cycle.

Figure 23 shows the series hybrid vehicle acceleration while climbing a slope. The vehicle is capable of starting on 14 percent grade with normal gear ratio.

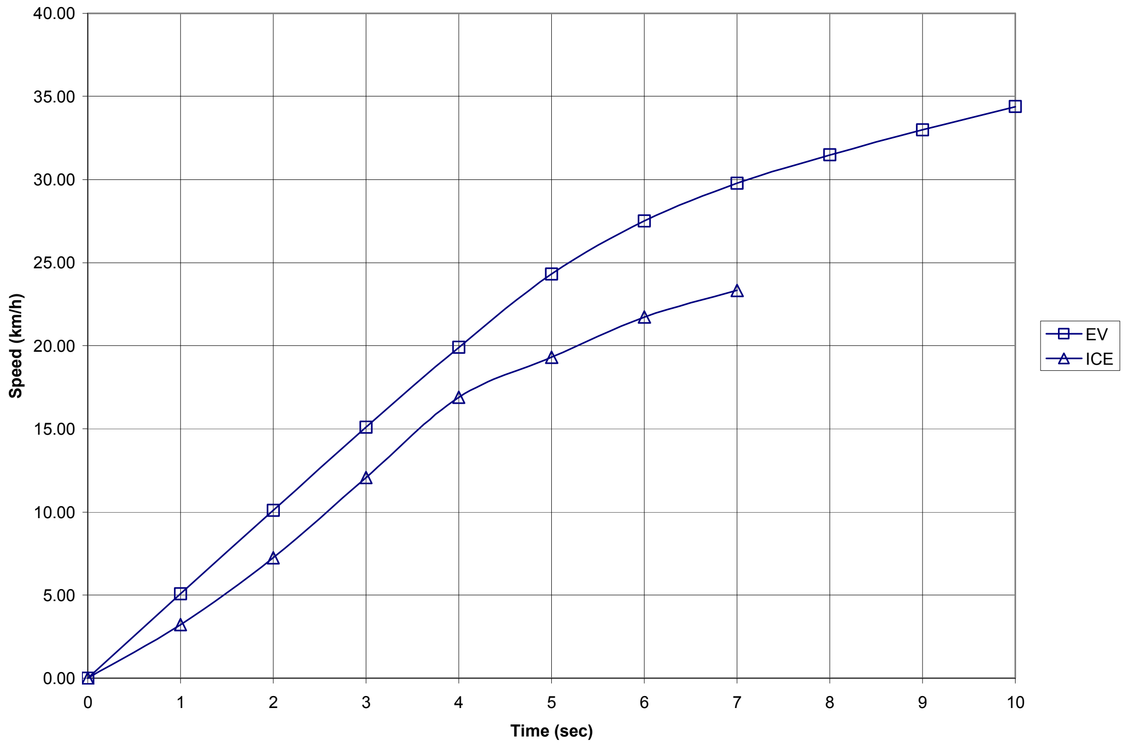

Figure 22: Acceleration – 150 kW Electric Drive vs. Actual Duty Cycle

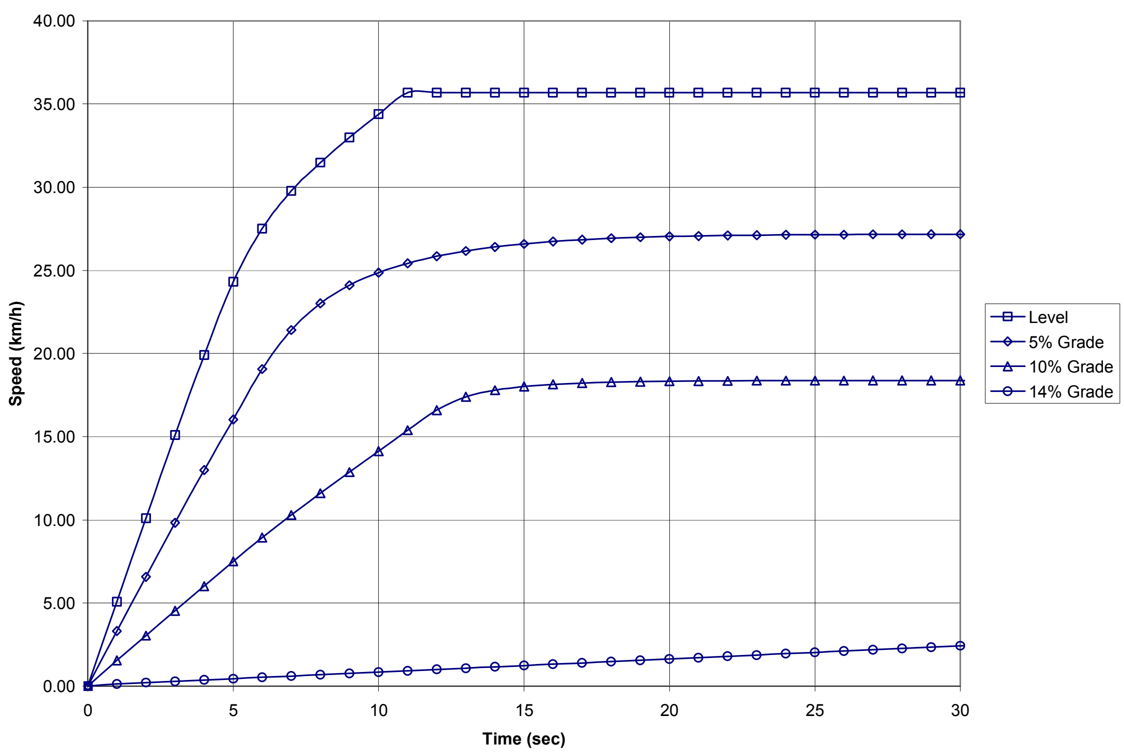

Figure 23: Gradeability of 150 kW Electric Drive

Hydraulic Powertrain

For hydraulic motors, the maximum torque developed by the motor is a function of the motor displacement and the system pressure, and is practically independent from the speed. Hence, the motor gearing will be different depending on whether the motor is in post- or pre-transmission configuration. Typically, the post-transmission configuration will require the speed reduction gear, as the motor operating range is above 500 rpm and to properly utilize the motor, the gear ratio should be between 3 and 4, depending on the pump size. The drive shaft speed of 500 rpm corresponds to the vehicle speed of approximately 19 km/h. By using the reduction gear with a factor of 3:1, the torque assist can be achieved at 7 km/h, and with ratio 4:1 – at 5 km/h. Higher gear ratios reduce the maximum speed at which the pump can operate. In the pre-transmission configuration, the hydraulic motor does not require an additional gear as the transmission input speed is significantly higher than that of the drive shaft (by a factor equal to the first gear ratio).

6.3 Performance Simulation – Summary

Analysis of the refuse truck performance is summarized as follows:

- Transfer mode torque/power requirements make series hybrid systems (series electric or hydrostatic) not practical – a conventional powertrain is the best option. Electric torque assist at transfer mode is useful but not critical.

- A properly geared lower power engine such as the Cummins ISB 260 hp could be used to reduce cost and weight and to improve efficiency in collection mode.

- A minimum 150 kW motor is needed in an electric dual mode system operating as series hybrid in collection mode. The overall gearing ratio for a typical induction machine should be in the order of 14:1.

- A minimum 90 kW motor is needed to fully recuperate the braking energy in a parallel system. An electric motor of that size would also allow the vehicle to stop using motor braking only, thus dramatically reducing the brake system loads.

- The startability of the series hybrid systems needs to be addressed. An electric series system can start the vehicle on a 14 percent grade with the transmission gearing designed for acceleration performance. Low gear or engine assist is needed to meet the startability criterion.

- In a parallel hydraulic system, the size of the motor depends on the torque capability in regeneration mode. Simulation studies indicated that a 130 cm^3 pump geared with a ratio of 3.5:1 would give the best efficiency on the assumed duty cycle.

- In a series hydraulic system, a 250 cm^3 motor is needed to provide sufficient drive torque. The series system should also include a 130 cm^3 pump.

6.4 Hybrid Systems Design

Based on the analysis of the performance data, the following powertrain system configurations were selected for analysis:

- Baseline Conventional System (ICE)
- Electric Parallel System (ETA)
- Electric Series System - Dual Mode (EDM)
- Hydraulic Parallel System - Torque Assist (HTA)
- Hydraulic Parallel System - Pressure Assist (HPA)
- Hydraulic Series System - Dual Mode (HDM)

Basic specifications of the modeled systems are shown in Table 4.

Table 4: Simulated Systems Specifications

	ICE	ETA	EDM	HTA/HPA	HDM
Engine	235 kW	235 kW	235 kW	235 kW	235 kW
Transmission	5 speed	5 speed	5 speed	5 speed	5 speed
Traction Motor		90 kW	180 kW	130 cm^3	250 cm^3
Motor Gear Ratio		14.1:1	14.1:1	3.5:1	3:1
Generator/Pump			120 kW		130 cm^3
Energy Storage		0.5 kWh	1.0 kWh	0.5 kWh	1.0 kWh

To maintain the ability to compare hybrid architectures, the engine and the transmission characteristics were assumed to be the same as for the baseline vehicle. However, in most systems the heavy duty engine and transmission can be replaced by lighter models to save weight and possibly cost. Smaller engines may also be more efficient in the collection mode in hybrid application. Note that the hydraulic pressure assist system requires a full size engine and transmission as it does not provide any torque assist to the powertrain.

7. ENERGY EFFICIENCY SIMULATION

A simulation of the energy efficiency of each system was carried out for three operating modes:

- Transfer to the route without load
- Collection on the route with variable payload
- Transfer to the landfill with full payload

The fuel consumed during transfers represents only a small fraction of the vehicle's overall fuel consumption. Approximately 85 percent of the fuel is consumed in collection mode. The effects of the system hybridization in transfer mode on the vehicle's overall fuel efficiency are an order of magnitude lower than in collection mode. It was therefore assumed that the vehicle operates as a conventional system in transfer mode, and the analysis focuses on collection mode.

The energy consumption of the hybrid systems operating in collection mode was simulated every 1000 kg for a constant weight ranging from 12,000 kg to 30,000 kg. This range covers the typical operating weight for refuse vehicles. It is also possible to investigate the effect of reduced vehicle weight by extrapolating the data.

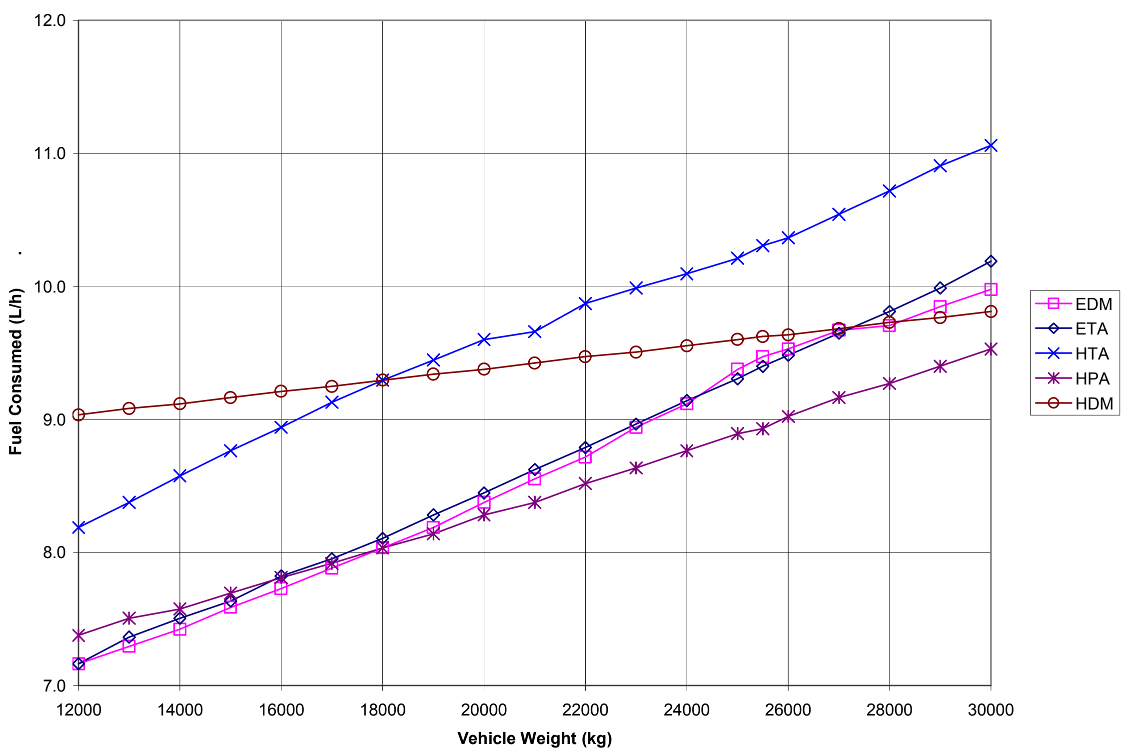

Figure 24: Simulated Fuel Consumption vs. Vehicle Weight

Figure 24 presents the fuel consumption data calculated for the Saint-Nicolas cycle as a function of vehicle weight. The fuel consumption is expressed in litres per hour of operation for a given weight.

The overall fuel consumption in collection mode was calculated by integrating the fuel consumption data from empty to full payload. The fuel consumption data for a full operating cycle for the reference vehicle (empty weight 14,000 kg, full weight 25,500 kg) are shown in Table 5.

Table 5: Simulated Fuel Consumption – Saint-Nicolas Route (L/cycle)

System Architecture	Transfer Mode - Empty	Collection Mode	Transfer Mode - Full	Cycle Total
Conventional (ICE)	2.5	41.9	2.5	46.9
Electric Parallel (ETA)	2.5	34.5	2.5	39.5
Electric Dual Mode (EDM)	2.5	34.3	2.5	39.3
Hydraulic Parallel (HTA)	2.5	38.9	2.5	43.9
Hydraulic Parallel (HPA)	2.5	33.8	2.5	38.8
Hydraulic Dual Mode (HDM)	2.5	38.3	2.5	43.3

Figure 25 presents the collection mode fuel consumption reduction relative to a conventional vehicle.

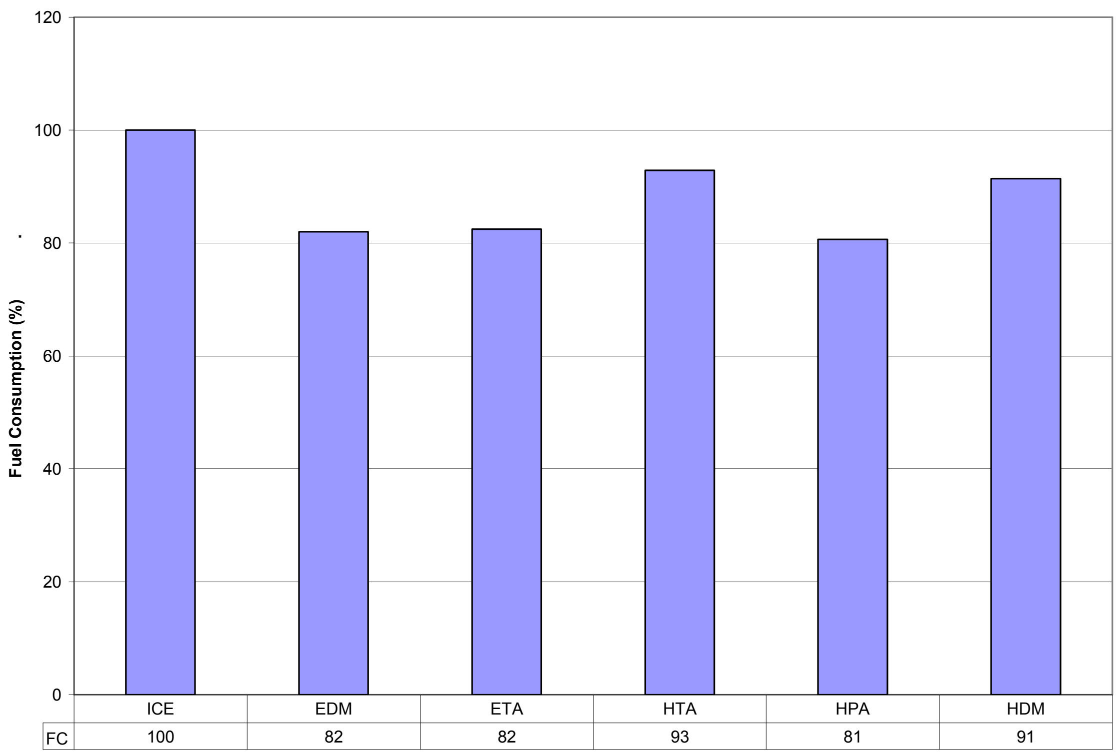

Figure 25: Fuel Efficiency of Hybrid Systems Compared to Baseline ICE Vehicle (Baseline ICE 100%)

The simulation results indicate that a fuel savings of approximately 18 to 19 percent can be achieved by three configurations – electric series, electric parallel and hydraulic parallel system with braking energy recovery to assist the hydraulic equipment.

It is worth noting that the pre-transmission electric parallel system has significantly lower efficiency than the post-transmission system (11 percent vs. 18 percent fuel reduction). This illustrates the importance of optimizing the motor for pre-transmission systems. In the analyzed case, both motors were identical and had been geared using the same ratios. If the transmission was locked in first gear, the results of the simulation would be identical. The difference in efficiency results from the transmission operating in second gear for a fraction of the cycle. In order to maximize efficiency, the motor gearing should be optimized for the transmission, or the transmission shifting control must be modified to operate in first gear.

Hydraulic systems that use the regenerative energy for traction (torque assist parallel and hydrostatic) have reduced potential for energy savings due to energy losses as a result of operating at reduced displacement and at speeds under 500 rpm.

8. WEIGHT

The weight penalty imposed by a hybrid system may be significant for some applications. This is due to the additional weight of the components, primarily the energy storage device. Table 6 presents an estimated weight breakdown of various hybrid systems compared to the baseline powertrain. The data shown assume that the baseline 320 hp engine and the heavy duty transmission will be replaced by lighter models in all systems with the exception of the hydraulic pressure assist system.

As shown in Table 6, only the parallel electric system can be designed to be weight neutral. All other hybrid systems impose a substantial weight penalty of 600 to 700 kg that represents almost 5 percent of the vehicle's curb weight. The extra weight will reduce the fuel consumption savings possible with these technologies by approximately 1 percent.

The effect of vehicle curb weight reduction on fuel consumption is shown in Table 7. It is assumed that the payload is the same for all three cases (12,000 kg).

From Table 7, the weight reduction effect is most significant for the conventional vehicle, at approximately 1.9 percent reduction in fuel consumption for each 1000 kg reduction in curb weight. For hybrid systems, the fuel savings are slightly lower, 1.5 to 1.7 percent per 1000 kg weight reduction. In absolute terms, the fuel savings due to curb weight reduction are in the order of 0.5 to 0.8 L of fuel per operating cycle. Since the vehicle is capable of collecting up to two loads per day, the annual fuel savings due to reduced curb weight would be between 200 and 400 L per 1000 kg weight reduction, depending on the type of the system and vehicle utilization.

Table 6: Conventional and Hybrid Powertrain Weight Comparison (kg)

Component	**ICE**	**ETA**	**EDM**	**HPA**	**HDM**
Engine	989	437	437	989	437
Transmission	405	261	261	405	261
Hydraulic Pump	40	40	40	40	88
Drive Motor		120	240	88	154
Drive Motor Gearing		50	75	50	75
Drive Motor Controller		72	72		
Starter/Generator			120		
Starter/Generator Controller			72		
Energy Storage System		91	180	275	550
ESS Electronics		75	75		
DC/DC Converter			40		
Auxiliary Motor - Steering			40		
Auxiliary Motor - Hydraulics			40		
Power Lines and Hardware		50	100	100	200
Control System		20	50	20	50
Cooling System		50	100	50	100
Miscellaneous Parts		100	200	100	200
Total Weight	**1,434**	**1,366**	**2,070**	**2,117**	**2,115**
Weight Penalty	**0**	**-68**	**+636**	**+683**	**+681**

Table 7: Fuel Consumption at Reduced Vehicle Curb Weight [L/payload]

System Architecture	Curb Weight 14,000 kg	Curb Weight 13,000 kg	Curb Weight 12,000 kg
Conventional (ICE)	41.9	41.1	40.3
Electric Parallel (ETA)	34.5	33.9	33.2
Electric Dual Mode (EDM)	34.3	33.7	33.0
Hydraulic Parallel (HTA)	38.9	38.3	37.7
Hydraulic Parallel (HPA)	33.8	33.3	32.8
Hydraulic Dual Mode (HDM)	38.3	38.1	37.9

It should be noted that the vehicles in heavier weight classes are limited by their GVW, and it is likely that by reducing the curb weight, the payload would be increased to the GVW limit. In the case of the refuse truck, that would increase vehicle productivity and require fewer trucks to service the particular area, resulting in more substantial savings to the operator as well as overall fleet energy and emissions reduction.

9. COST

A hybrid vehicle will always carry a price premium compared to a similar conventional vehicle due to the additional components required in a hybrid powertrain. For mass produced hybrid cars and light trucks, the purchase premium is currently approximately 20 to 25 percent of a comparable conventional vehicle price. That represents US$5,000 to $10,000 over the price of the base vehicle. However, with rapidly increasing production volume of hybrid vehicles, the cost premium is expected to drop to a minimum within a few years.

In the medium and heavy duty vehicle sector, hybrid powertrains command a much higher premium. The cost premium for hybrid buses has been reported to be in the range of US$115,000 to $250,000, a 50 to 100 percent increase over the price of a comparable diesel bus. Hybrid technology in transit buses is primarily driven by emissions regulations, as fuel and maintenance savings are not sufficient to offset the high cost of the hybrid drive. In contrast, hybrid delivery vans are already commercially viable. Aggressive cost engineering, combined with high fuel prices, has resulted in payback times approaching three years for hybrid delivery vehicles.

In the case of the refuse truck, the price of a baseline refuse truck is approximately US$170,000. A CNG version is available at US$210,000 [1]. Both diesel and CNG options are mature technologies, benefiting from economy of scale. Existing heavy duty hybrid propulsion options suitable for refuse trucks range from approximately US$30,000 for a simple parallel assist system to US$300,000 for an advanced series-parallel system.

In order to evaluate the commercial viability of a hybrid refuse truck, a simplified economic model was developed that included an analysis of the cost of the system and potential operating savings. The objective of the analysis was to determine whether it is feasible to build a hybrid system at a cost premium sufficiently low to provide a reasonable payback time (two to three years).

The cost model included an analysis of major components costs, overall system costs for various powertrain configurations and prototype development costs. In the final payback analysis, the labour cost component and the manufacturer's margin were factored into the price premium calculations. The payback time was calculated based on fuel savings derived from simulation data and maintenance cost savings estimated from available user data. To simplify the interpretation of the results, the costs were analyzed using U.S. dollars, as the majority of the components and vehicle prices are typically quoted in that currency.

9.1 Component Cost

The cost of powertrain components depends primarily on production volume. In particular, for electric powertrain components, a cost of a one-off component for prototyping can be significantly higher than for the production model. Hydraulic component prices are easier to estimate, as most components are manufactured in volume and their list prices are available. For this analysis, two cost levels were assumed – a prototyping price and a low-volume production price. The prototype price is based on current estimates of a component cost based on published information. The production price estimate takes into account potential volume discounts and factors in a projected cost reduction for new technologies based on analysis of industry trends.

Electric Machines

In recent years, a number of electric motors for heavy vehicle application have been introduced commercially. Two types of technologies prevail for the hybrid vehicle application – AC induction motors and brushless DC permanent magnet motors. Induction motors have been used in the industry for years and are the primary choice for traction applications. Permanent magnet technology is widely used in the small motors industry. Permanent magnet motors are used primarily as generators in hybrid systems. Induction motors have been traditionally about 30 percent cheaper than permanent magnet machines of the same size, but recently the cost difference is narrowing due to the rapid increase in the cost of steel and copper and the decreasing costs of permanent magnet materials.

Table 8 presents specific parameters of several electric motor models currently available for heavy duty vehicle traction that meet the requirements of the hybrid refuse truck powertrain.

Table 8: Specifications of Selected Electric Motors and Generators

Model	ISE/Siemens	ISE/Siemens	Solectria AC90	Solectria AC120
Type	AC Ind	PM Synch	AC Ind	AC Ind
Nom Voltage (V)	650	650	336	336
Rated Power (kW)	85	120	45/125	60/156
Rated Torque (Nm)	220/450	320/450	90/875	200/935
Max Speed (rpm)	9000	4000	4500	4500
Volume (L)	31	31	64	64
Weight (kg)	120	120	189	257

The unit costs of traction motors discussed in technical literature are not consistent and vary from US$5 to $75/kW. For budgetary purposes, it was assumed that for a single unit order, the unit cost will be higher, at US$100/kW, while for a small-scale production volume, the cost will be US$75/kW. Based on these assumptions, an advanced 85 kW

AC induction motor will cost approximately US$8,500 for a single unit, while a production volume unit would cost US$6,400. The high cost of traction motors could significantly drop, however, with increasing production to a level of US$2,000 to $3,000 for a 100 kW-class machine.

Electric Energy Storage

The energy storage device for a refuse truck application must be capable of withstanding a large number of cycles beyond the capabilities of present batteries. Ultracapacitor technology appears more suitable for this application. The technology is developing very fast and, in recent years, several manufacturers have introduced large ultracapacitor packs for heavy duty applications.

Specifications of two commercially available ultracapacitor packs are shown in Table 9 [29,30].

Table 9: Specifications of Selected Ultracapacitor Packs

Model	ISE Thundervolt II	Nesscap 51F/340V
Cell Manufacturer	Maxwell	Ness Capacitors
No of Cells	144	272
Cell Capacity (F)	2600	3500
Pack Capacity (F)	18.05	51.4
Nominal Voltage (V)	360	340
Energy Capacity (kWh)	0.407	0.960
Max Power (kW)	150	1000
Total Volume (L)	189	416
Total Weight (kg)	91	384

Ultracapacitors are still more expensive than batteries. The price of the ISE Thundervolt II pack of 144 cells is reported in the order of US$10,000. However, some manufacturers have announced a near-term cost target at the level of US$0.01/F. The volume price of a 2600 F Maxwell cell has been recently reported as US$27 and is expected to drop by half by 2010 [31]. The cost of a 144-cell pack similar to the ISE unit could be as low as US$2000. In the near future, a realistic assumption for a 0.5 kWh pack cost would be approximately US$5000. Considering the long life of the ultracapacitors, the technology may offer an economic advantage over batteries, which would have to be replaced two or three times during the lifetime of the vehicle.

Hydraulic Motor-Pumps

Hydraulic pumps and motors are readily available and widely used in the industry. For the purpose of this analysis, a range of variable displacement machines manufactured by Sauer Danfoss were investigated to model hydraulic hybrid drives. Basic specifications of the Series 90 motors/pumps, including the prices in prototype and small production volumes, are shown in Table 10 [23].

Table 10: Specifications of Selected Variable Displacement Pumps Motors

Model	055	075	100	130	180	250
Displacement (cm^3/rev)	55	75	100	130	180	250
Max torque (Nm)	303	410	548	714	990	1370
Weight (kg)	40	49	68	88	136	154
Volume (L)	14.5	16.1	21.0	25.6	32.9	34.6
Maximum speed (rpm)	4250	3950	3650	3400	2850	2500
Price 1x (CAD$)	2,369.78	2,591.35	2,912.96	4,222.68	6,860.37	8,551.46
Price 50x (CAD$)	2,132.80	2,332.22	2,621.67	3,800.41	6,174.33	7,696.31

Hydraulic Energy Storage

Hydraulic energy storage devices are also manufactured commercially. Within the scope of this study, several products manufactured by Hydac were used to model hydraulic pressure accumulators. Basic specifications of the Hydac models are shown in Table 11 [26].

Table 11: Specifications of Selected Pressure Accumulators

Model	SK600 50	SK600 75	SK600 30+56L N_2	SK600 20+56L N_2
Pressure P1 (psi)	1700	2500	3800	3500
Capacity (Wh)	130	145	380	208
Total Volume (L)	107	232	145	126
Total Weight (kg)	401	731	435	363
Price 1x (CAD$)	7,807.00	11,785.00	7,145.00	5,818.00
Price 10x (CAD$)	5,943.00	9,413.00	5,280.00	3,953.00

9.2 System Cost Projections

Tables 12 to 15 present an estimated system cost breakdown for hybrid refuse truck propulsion systems (not including the engine and transmission).

Table 12: Electric Parallel Hybrid Cost Model

Component	Description	Prototype Price US$	Production Price US$
Drive motor	Siemens 85 kW	8,500	5,000
Drive motor gearing	single speed gearbox	1,000	800
Drive motor controller	Siemens	4,000	2,000
Energy storage system	ISE Thunderbird II	10,000	5,000
ESS slectronics		2,000	1,000
Power lines and hardware		2,000	1,000
Control system		2,000	1,000
Cooling system		3,000	2,000
Misc parts		2,000	1,000
System Total		**34,500**	**18,800**

Table 13: Electric Dual Mode Hybrid Cost Model

Component	Description	Prototype Price US$	Production Price US$
Drive motor	2xSiemens 85 kW	17,000	10,000
Drive motor gearing	single speed gearbox	2,000	1,000
Drive motor controller	Siemens	4,000	2,000
Starter/Generator	Siemens 120 kW	10,000	5,000
Starter/Generator controller	Siemens 120 kW	2,000	1,000
Energy storage system	2x ISE Thundelvolt II	20,000	10,000
ESS electronics		2,000	1,000
DC/DC converter		2,000	1,000
Auxilary motor (steering)		2,000	1,000
Auxiliary motor (hydraulics)		5,000	3,000
Power lines and hardware		2,000	1,000
Control system		2,000	1,000
Cooling system		3,000	2,000
Misc parts		2,000	1,000
Totals		**75,000**	**40,000**

Table 14: Hydraulic Parallel Hybrid Cost Model (Pressure-Assist)

Component	Description	Prototype Price US$	Production Price US$
Drive motor/pump	Sauer-Danfoss S90-130 cm^3	3,500	3,000
Drive motor gearing	single speed gearbox	2,000	1,000
Energy storage system	Hydac SK 6000 30+56	6,000	4,000
Power lines and hardware		2,000	1,000
Control system		2,000	1,000
Cooling system		5,000	3,000
Misc parts		2,000	1,000
Totals		**22,500**	**14,000**

Table 15: Hydraulic Dual Mode Hybrid Cost Model

Component	Description	Prototype Price US$	Production Price US$
Hydraulic pump*	Sauer-Danfoss S90-130 cm^3	1,500	1,000
Drive motor	Sauer-Danfoss S90-250 cm^3	6,500	5,000
Drive motor gearing	single speed gearbox	2,000	1,000
Energy storage system	2xHyDac SK 6000 30+56	12,000	8,000
Power lines and hardware		2,000	1,000
Control system		2,000	1,000
Cooling system		5,000	3,000
Misc parts		2,000	1,000
Totals		**33,000**	**21,000**

* A larger pump is needed in a hydraulic system as it has to provide the hydraulic equipment pressure and supply the traction motor. The figure shown in the table reflects the price difference between the original pump and the larger pump.

9.3 Development Cost Projections

The development costs of a hybrid powertrain are an important element of the overall system cost for small volume production. Tables 16 and 17 identify the major tasks of the development process for a proof-of-concept and production prototype. A rough estimate of each task cost is also shown. The task cost estimates include direct costs such as labour, components and supplies procurement. The development costs shown here are for a simpler system such as a post-transmission parallel or series architecture. The development cost for configurations that require extensive vehicle modifications, such as pre-transmission systems, may by substantially higher.

Table 16: Proof-of-Concept Prototype Development Cost

Task	Estimated Cost US$
Prototype System Design	100,000
Component Procurement	50,000
Detailed Design	100,000
Component Manufacturing	50,000
System Integration	100,000
Control System Development	200,000
System Calibration	100,000
Prototype Testing	100,000
Proof-of-Concept Cost	**800,000**

Table 17: Production Prototype Development Cost

Task	Estimated Cost US$
Detailed Re-design	300,000
FMEA	50,000
Component Procurement	50,000
Tooling Development	500,000
Component Manufacturing	50,000
System Integration	100,000
System Calibration	100,000
Test and Validation	200,000
Certification	150,000
Production Prototype Cost	**1,500,000**

It must be emphasized that the development cost model presented here is intended as a starting point for a detailed analysis of a specific design. The cost structure will depend on the system integrator's experience, their resources, labour rates, etc. The cost figures shown here represent a rather optimistic scenario and in the more detailed analysis, a substantial contingency factor should be applied.

9.4 Operating Savings

Fuel consumption reduction is the key element in achieving commercial viability of the technology, as it is the major cost savings factor. The only other factor directly affecting the operating costs is reduced maintenance costs (primarily brake servicing).
Other benefits of a hybrid system to the operator, such as a reduced pollution and noise, improved performance, etc., are not readily quantifiable, although in some cases these may be significant. In particular, the reduction in emissions may have a measurable benefit if the industry is regulated as in California. However, the incentives vary locally and may not be permanent. Consequently, only the fuel and maintenance savings were used to estimate payback time for each proposed system.

Fuel Savings

The vehicle simulation models developed for this study are generic, and detailed optimization of the system was not possible. It is to be expected that the production hybrid powertrains will be highly optimized for specific hardware configuration, duty cycle, etc. However, the simulated models reflect the physics of the vehicle and it is not likely that the optimized system will be dramatically better than the concepts presented in this study. The optimization potential depends on the system architecture. As a general rule, electric systems are easier to optimize than hydraulic ones because of their higher flexibility and wider diversity of available technologies. Dual mode or series systems are easier to optimize than parallel as the engine is decoupled form the wheels and offers more control flexibility.

The analysis of potential fuel savings achievable by hybridization was conducted first for the fuel consumption data obtained directly from the simulation and subsequently for hypothetical optimized systems. The fuel savings achievable for optimized systems were estimated based on the qualitative analysis of each technology. The simulated fuel savings results for parallel electric, dual mode electric and parallel hydraulic (pressure assist) systems were in the order of 18 percent. It is possible that by optimizing the system, this can be improved up to 25 percent. In the case of the hydraulic dual mode system, the calculated fuel savings were 9 percent, and it is estimated that 15 percent savings can be realized with an optimized system.

Tables 18 and 19 present the analysis of the potential fuel savings for various hybrid truck options using the Saint-Nicolas cycle as an example of a typical route. The analysis was based on the following assumptions:

- The baseline fuel consumption is for a conventional vehicle operating on collection cycle only. Potential savings in transfer mode were not included.

- The vehicle can complete two routes (full payloads) per day, 250 days a year.

- The fuel cost used to calculate annual fuel savings is US$0.70/litre (US$2.66/gallon). This represents typical retail diesel fuel price in the U.S. as of

August 2005. In some areas such as California, the diesel fuel price is closer to US$0.80/litre (US$3.04/gallon) [32]. Fuel prices increased by nearly 40 percent in the period between August 2004 and August 2005 and, although seasonal price drops are possible, the long-term fuel price trend is a gradual increase. Over the lifetime of the vehicle, the fuel price will likely increase, shortening the payback time. The sensitivity of payback time to fuel cost increase is discussed in section 9.5.

Table 18: Hybrid Truck Fuel Savings vs. Baseline Vehicle (Simulated Data)

	ETA	EDM	HPA	HDM
Fuel consumed/route (litres)	42	42	42	42
Routes/day	2	2	2	2
Fuel consumed/day (litres)	84	84	84	84
Fuel savings (%)	18	18	19	9
Fuel savings/day (litres)	15.1	15.1	16.0	7.6
Number of working days	250	250	250	250
Fuel savings/year (litres)	3780	3780	3990	1890
Fuel price (US$/litre)	0.7	0.7	0.7	0.7
Savings on fuel/year (US$)	2,646	2,646	2,793	1,323

Table 19: Hybrid Truck Fuel Savings vs. Baseline Vehicle (Optimized System)

	ETA	EDM	HPA	HDM
Fuel consumed/route (litres)	42	42	42	42
Routes/day	2	2	2	2
Fuel consumed/day (litres)	84	84	84	84
Fuel savings (%)	25	25	25	15
Fuel savings/day (litres)	21	21	21	12.6
Number of working days	250	250	250	250
Fuel savings/year (litres)	5250	5250	5250	3150
Fuel price (US$/litre)	0.7	0.7	0.7	0.7
Savings on fuel/year (US$)	3,675	3,675	3,675	2,205

Maintenance Savings

The additional components of a hybrid system, either electric or hydraulic, require very little maintenance. It can be reasonably assumed that the hybrid powertrain maintenance cost is the same as for the conventional vehicle. Some savings can be realized by less frequent engine oil and transmission fluid changes, although these are likely not very significant and are not included in the payback analysis. Brake servicing is typically the main maintenance cost savings factor for hybrid systems. All hybrid systems discussed in this study were designed to provide maximum capability for regenerative braking using the motor only. The mechanical brakes would be used only at low speeds in the final stage of deceleration. For the purpose of this analysis, it was assumed that the annual cost savings on brake maintenance are in the order of 50 percent, approximately US$1000.

9.5 Payback Estimates

A reasonable payback time for investment in a new technology is generally accepted to be two to three years. In the case of hybrid technology, the initial vehicle purchase premium must be offset by savings on fuel and maintenance within that period of time. Most of the present commercial hybrid vehicles do not meet the payback criteria. The main challenge is in the high cost of components at low volume production.

In order to assess the economics of hybrid system implementation in a refuse truck, a cost-benefit model was developed to calculate the payback time for the presented hybrid options. The main assumptions of the analysis, shown in Tables 20 and 21, were:

- Hybrid system cost (not including the engine, transmission and main hydraulic pump) for production systems is as calculated in Section 8.2.
- For torque-assist systems it is possible to use a lighter engine and transmission. Potential cost savings are estimated at US$4,000. This option is not possible for a hydraulic pressure assist system.
- Development costs per unit are based on 1000 units required to recover the development costs (Section 8.3).
- The labour cost is 20 percent of the cost of all components.
- The margin is 15 percent.
- Fuel and maintenance savings are as calculated in Section 8.4.
- Payback time is calculated by dividing the cost premium by annual operating cost savings.

Table 20 shows the analysis based on the net fuel consumption reduction calculated using simplified simulation models. Table 21 shows potential cost savings and payback time for optimized systems.

Table 20: Payback Time Based on Simulation Data (fuel cost US$0.70/litre)

	ETA	EDM	HPA	HDM
Hybrid System Cost (US$)	18,800	40,000	14,000	21,000
Engine/Trans. Savings (US$)	4,000	4,000	0	4,000
Net System Cost (US$)	14,800	36,000	14,000	17,000
Labour Cost (US$/unit)	3,000	7,200	2,800	3,400
Development Costs (US$/unit)	2,300	2,300	2,300	2,300
Manufacturing Cost (US$)	20,100	45,500	19,100	22,700
Margin 15% (US$)	3,000	6,800	2,900	3,400
Total Price Premium (US$)	**23,100**	**52,300**	**22,000**	**26,100**
Fuel Savings/year (US$)	2,646	2,646	2,793	1,323
Maintenance Savings/year (US$)	1,000	1,000	1,000	1,000
Total Savings/year (US$)	**3,646**	**3,646**	**3,793**	**2,323**
Payback Time (years)	**6.3**	**14.3**	**5.8**	**11.2**

Table 21. Payback Time Based on Optimized System Estimates (fuel cost US$0.70/litre)

	ETA	EDM	HPA	HDM
Hybrid System Cost (US$)	18,800	40,000	14,000	21,000
Engine/Trans. Savings (US$)	4,000	4,000	0	4,000
Net System Cost (US$)	14,800	36,000	14,000	17,000
Labour Cost (US$/unit)	3,000	7,200	2,800	3,400
Development Costs (US$/unit)	2,300	2,300	2,300	2,300
Manufacturing Cost (US$)	20,100	45,500	19,100	22,700
Margin 15% (US$)	3,000	6,800	2,900	3,400
Total Price Premium (US$)	**23,100**	**52,300**	**22,000**	**26,100**
Fuel Savings/year (US$)	3,675	3,675	3,675	2,205
Maintenance Savings/year (US$)	1,000	1,000	1,000	1,000
Total Savings/year (US$)	4,675	4,675	4,675	3,205
Payback Time (years)	4.9	11.1	4.7	8.1

Table 22 presents the results of an analysis of the effect of fuel price on payback time.

Table 22. Effect of Fuel Price on Payback Time (Optimized System Estimates)

Fuel Price (US$/litre)	Fuel Price (US$/gallon)	ETA	EDM	HPA	HDM
0.60	2.28	5.5	12.6	5.3	9.0
0.70	2.66	4.9	11.1	4.7	8.1
0.80	3.04	4.1	10.0	4.2	7.4
1.00	3.80	3.7	8.4	3.5	6.2
1.20	4.56	3.2	7.2	3.0	5.5

10. MARKET ACCEPTABILITY

10.1. Market Drivers

The current market drivers for the use of hybrid technology are:

- Noise: Because collection is often done early in the morning when there is no traffic, cities are sensitive to noise levels of their collection vehicles.
- Air pollution: The quality of air in large cities has declined rapidly and dramatically in the past ten years. Smog and the ozone are the main concerns.
- Operating costs: Fuel prices are constantly rising and cities and haulers are concerned with the increasing effect this has on their operating costs.

10.2 Market Volume

There are close to 10,000 refuse vehicles (the majority of them Class 8 units) sold in North America per year. A survey conducted among industry leaders in February 2005 by the West Start organization identified the projections shown in Table 23 for the refuse truck market.

Table 23: Refuse Truck Market Projections

Powertrain Type	2010	2020
Diesel	80.7%	65.4%
Natural Gas	7.7%	10.6%
Hybrid	8.9%	18.4%
Fuel Cell	1.9%	4.4%
Hydrogen ICE	1.3%	4.2%

Équipement Labrie estimates that the demand for hybrid refuse vehicles will be 500 to 1000 units in 2010, and 1000 to 2000 units in 2020.

11. DISCUSSION

Existing Hybrid Powertrain Options

Existing hybrid hydraulic systems are not yet commercially available. Eaton Corporation has the capability to commercialize the systems within two to three years. As a major OEM supplier, Eaton has the capacity to manufacture and support its products. Other players, including Dana, appear to lag behind Eaton in their development and commercialization efforts.

Dual mode electric/diesel trucks prodcuced by PVI have an inherent disadvantage of requiring a heavy and expensive battery pack that reduces the payload and produces a serious packaging challenge. The 96 V system used by PVI appears to be rather inefficient and lacking in performance to compete with modern conventional trucks.

Hybrid transit bus drives can be adapted to refuse truck applications. Allison's system is the most advanced option available and its specifications meet the requirements of a refuse truck. The advantages of the Allison system are that it has been thoroughly engineered by an OEM, it is likely to achieve adequate reliability and technical support, and in the long term it will benefit from economy of scale. Allison has been very successful in marketing its product and its customer base is growing rapidly. The disadvantage of the Allison system is its high purchase cost and potentially high engineering cost to adapt the system for a refuse truck.

Heavy duty truck and bus drives can be adapted to power a refuse truck with various levels of engineering effort. The BAE/Orion system has the longest track record of all hybrid bus system suppliers as its buses have been in commercial operation for New York Transit since 1998. However, the system is built specifically for a transit bus and may not be available for other applications. Other hybrid bus powertrain manufacturers offer a variety of components suitable for hybrid refuse truck propulsion. Among the reviewed suppliers, ISE appears to have the components most suitable for a refuse truck system. The main issue with the heavy duty systems suppliers is the reliability and support that has not yet reached the maturity of major OEMs. Siemens components, distributed by ISE, are most likely to achieve OEM levels of production quality.

Operating Performance

The dynamics of a vehicle with a parallel system are superior to a conventional vehicle with the same engine. The acceleration and gradeability are substantially improved as the overall torque on the wheel is increased at lower speeds.

The performance of a series system with the motor providing full traction torque is comparable to that of the baseline vehicle. The acceleration profile can be improved by using electric traction. The simulation shows that a 150 kW motor has an acceleration capability similar to a 230 kW diesel engine. The main limitation of the series system is its gradeability. The assumed 150 kW motor operates up to a 10 percent grade. At high grade route sections, either a low gear option or engine assist would be necessary.

The analysis of power requirements in transfer mode indicates that a smaller engine (e.g., a 260 hp Cummins ISB model) would be sufficient to meet highway speed and gradeability criteria. In collection mode, the hybrid systems would still provide adequate acceleration while reducing the dynamic loads on the engine. Similarly, a regular duty transmission could be used, particularly for post-transmission configurations. However, for the hydraulic pressure assist system, this option is not available, as the hydraulic pump does not provide any direct engine assist during acceleration.

Energy Efficiency

Analysis of energy consumption for the selected duty cycle indicates that approximately 60 percent of energy is used for traction and 40 percent for refuse handling. As a result, hybridization of the powertrain has a lesser effect on overall fuel consumption than for applications such as a transit bus or a delivery truck.

Simulation results indicate that the efficiency of an electric parallel system and a series system is almost identical, at approximately 18 percent fuel consumption reduction in collection mode compared to a conventional truck. This is equivalent to 30 percent savings on traction energy consumption. It is likely that by optimizing the systems, this can be further improved up to 23 to 25 percent (equivalent to approximately 40 percent of traction energy requirements).

Hydraulic pumps and motors have a disadvantage of lower efficiency at low speeds and low loads. Despite higher efficiency of energy storage compared to electric devices, the simulated efficiency improvement of hydraulic systems that provide traction assist was lower than comparable electric systems, at 7 percent for a parallel system and 9 percent for a hydraulic dual mode. It is likely that by optimizing the system, this can be improved to 12 to 15 percent. However, a hydraulic system that utilizes the braking energy to assist the hydraulic equipment rather than the engine was found to be highly effective, reducing fuel consumption by 19 percent. This indicates that reduction of hydraulic system load on the engine is a very effective means of reducing fuel consumption, as the hydraulic energy is generated at poor efficiency conditions of the engine. Almost 50 percent of the system's hydraulic energy needs were satisfied by recuperated braking energy.

Emissions

Emissions reduction for parallel systems is, for practical purposes, proportional to the fuel savings. For heavy duty diesel engines, the reduced engine load at low speeds is likely to further improve particulate matter emissions.

In series systems, emissions can be more effectively controlled than in parallel systems. In the case of series hybrid buses, greenhouse gas emissions are basically in line with fuel savings, but the ozone-forming emission components are reduced by up to 90 percent. However, in the refuse truck case, the fuel savings are lower than for a bus and the engine operates at unfauvorable conditions for significantly larger share of the time. As a result, emissions reduction will be more modest than for a bus system, but still significantly better than for parallel drives.

In absolute terms, it is possible to reduce annual carbon dioxide emissions from a single truck by approximately 13 metric tons (equivalent to 5000 litres of saved diesel fuel). Assuming that the entire refuse truck fleet in Canada could be converted to achieve similar fuel efficiency, the annual reduction in greenhouse gas emissions would amount to approximately 200,000 metric tons.

Detailed quantification of ground-level emissions from hybrid refuse trucks was not possible within the scope of this study and further work is needed to assess emissions benefits.

Particulate matter (PM) emissions from heavy duty diesel engines are of particular concern due to their health risks. CARB regulations will require fleet operators to use best available technology with a target to reduce PM emissions by 85 percent to at least 0.01 g/bhp-hr by 2015 (compared to 2000 levels) [33]. Although all hybrid systems significantly reduce PM emissions, it is likely that advanced particulate filters may have to be used to achieve CARB targets.

Noise

Noise emissions from a parallel system are somewhat lower than for a comparable diesel truck, primarily due to lower engine load during acceleration. Modern electric traction motors are relatively quiet and the combined noise emissions of the systems will be lower. However, since the hydraulic pump is driven from the engine, the engine noise profile during loading and compacting will not be affected.

A series system has significant potential for noise emissions reduction thanks to the capability of independent engine control and the possibility of using electric motors to drive hydraulic pumps.

Direct noise comparisons between electric and hydraulic hybrids are not possible due to the lack of relevant operating data. However, the EPA has identified the noise issue as one of the problems to be addressed in development of its hydraulic technologies. On the other hand, experience with electric hybrids indicates that electric drives can reduce the overall noise level of the vehicle. It has been reported that the noise level of a hybrid bus equipped with an Allison series-parallel powertrain is significantly lower than that of a conventional bus.

System Integration

Series systems and post-transmission parallel systems are relatively easy to integrate, as they do not require major changes to the conventional powertrain. The control effort for component control and energy management is also within the capability of non-OEM system integrators. Parallel systems are somewhat more difficult to control than series systems, as the traction power share between the motor and the engine has to be controlled in real time.

Pre-transmission systems are substantially more difficult to integrate, as they involve modifications to the original powertrain and often require custom-designed motors and gearing. The pre-transmission systems also require higher control effort, as the transmission and engine control strategy has to be included in the system control algorithm. The example is regenerative braking, which has to be done through the gears; the motor characteristics must therefore be matched to the transmission input shaft speed profile. On the upside, pre-transmission systems offer more elegant and compact packaging and operate more effectively through the vehicle's entire speed range. In the case of the refuse truck in collection mode, this is not critical because the vehicle operates primarily in first and second gear only.

The series-parallel system requires an extensive engineering effort that makes it not practical to develop a dedicated system for a refuse truck only. This option is not viable for a non-OEM developer and the only practical approach is to use an OEM system such as Allison, customized for refuse truck application, preferably by the system manufacturer. Given present cost of the Allison system, in vicinity of US$300,000, it appears that the operating savings possible for a refuse truck do not justify the cost premium.

The behaviour of electric hybrid systems in road vehicles is reasonably well understood. Hydraulic systems have typically been used in industrial and off-road applications where the energy efficiency, emissions, noise and cost constraints are less stringent than for road vehicles that must compete with volume-manufactured conventional powertrains. The mechanical characteristics of hydraulic motors and pumps are unfavourable under 500 rpm and the systems must be geared to ensure operation at low vehicle speed. However, the operating speed range of the geared machines is reduced and a clutch may be required to decouple the hydraulic motor at highway speeds.

For a hydraulic system to be practical, the nominal operating pressure must be at least 5000 psi. As a result, all components must be designed for high pressure, resulting in higher cost and higher probability of failure than for typical 3000 psi systems. The . consequences of failure of highly pressurized components can be very dramatic and the issue of pressure vessel certification for frequent pressure cycling must be thoroughly investigated. Leaks are also more frequent at high pressure, leading to potential maintenance problems and diminished vehicle appeal.

Component packaging is a significant challenge in the case of a refuse truck, as the hydraulic equipment uses most of the chassis space that in other applications is available for the hybrid powertrain. Detailed analysis of space allocation is possible only for a specific truck and chosen powertrain option. In general, electric components appear to be more compact than hydraulic, and the electric system is more flexible so its elements can be distributed according to available space.

For both the electric and hydraulic systems, large amounts of heat are generated due to the energy losses in the components. Cooling is a major design challenge in hybrid vehicles. High power electric drives are liquid-cooled and require a dedicated low-temperature cooling circuit. Batteries and ultracapacitors are air-cooled and must be provided with sufficient air flow to remove the heat. A hydraulic system would require an additional oil cooler to account for the increased heat from the motor and the pressure accumulator.

Installation and Maintenance

Hydraulic systems have the advantage over electric with regard to installation and maintenance. Refuse truck manufacturers and operators have required skills and expertise in working with hydraulic components. Manufacturers have also safety and troubleshooting procedures in place for hydraulic equipment. Due to the safety issues, the high power electric systems have to be handled by specially trained staff and may require specialized test and maintenance equipment.

Cost

The simplified cost analysis presented in Section 8 indicates that parallel systems (electric torque assist and hydraulic pressure assist) are commercially viable, requiring only approximately 4 years of payback time at current fuel prices. The cost premium for both systems is significantly less than the premiums for CNG and LPG systems, which are estimated at US$40,000 to $50,000 [1,34]. Even with an advanced particulate system that costs up to US$10,000 (CARB estimates) [33], a parallel system would offer an attractive alternative to those fuels. It is plausible that the fuel cost will increase even further, making the hybrid option more attractive.

Dual mode systems are significantly more expensive and require a payback of 8 (hydraulic) to over 10 years (electric). This is due to the more complex system architecture, requiring more components but potentially offering improvements in many areas beyond fuel consumption. The total premium for a dual mode system (electric: US$52,000) is still within the realm of the CNG and LPG systems, but the former is capable of significantly better performance, emissions reduction and fuel consumption savings.

Weight

The weight analysis was conducted under the assumption that a lighter engine and transmission could be used in a hybrid system. By using a 5.9 L engine and a standard transmission, the weight could be reduced by 700 kg. This is sufficient to offset entirely the added weight of a parallel system. A dual mode system would still require some weight premium, in order of 600 to 700 kg. That would represent approximately a 5 percent reduction in payload or approximately 1 percent lower fuel efficiency if this were added to the total weight of the vehicle.

Commercial Viability

Based on the analysis of the simulation data and general benefits and disadvantages of each technology, a simple evaluation matrix (Table 24) was created to assess the relative merits of each technology. The scoring system assumed a scale of 1 to 4 for each technology (1 - poor, 2 - satisfactory, 3 - good, 4 - very good) and weighting factors for each criterion (also as a scale of 1 to 4, where 1 is not very important, 2 is somewhat important, 3 is important, and 4 is very important). The maximum possible combined score was 100 points. Obviously, the total score depends strongly on the weighting factors assigned subjectively to each criterion. In this case, the maximum weights were assigned to the energy efficiency and cost of the system as these factors determine the commercial viability of each system.

Table 24. Technology Evaluation Matrix

Evaluation Criteria	**Weight**	**ETA**	**EDM**	**HPA**	**HDM**
Energy Efficiency	4	4	4	4	2
Performance	3	4	3	4	3
Emissions	3	2	4	2	3
Noise	3	2	4	2	3
Implementation	3	4	2	4	3
Maintenance	2	3	3	4	4
Weight	2	4	2	3	3
System Cost	4	4	2	4	2
Development Effort	2	3	2	4	3
Total Score (out of 100)		**84**	**75**	**86**	**69**

The results of the evaluation confirm the intuitive assessment, identifying the parallel hydraulic system with braking energy recovery used to assist the hydraulic equipment as the most viable technology to achieve the objective of maximum operating savings at minimum cost.

12. CONCLUSIONS

Due to the specific features of a refuse truck – large engine, very high stopping frequency, and continuous hydraulic power demand – the hybrid refuse truck powertrain relies primarily on braking energy recovery to reduce fuel consumption. Parallel hybrid systems are able to achieve energy savings comparable to a series system. Since the cost and weight penalty is much lower for parallel systems, the series systems are at a disadvantage for this application.

The results of the study indicate that hydraulic systems have lower energy efficiency than advanced electric systems. However, lower cost and simpler implementation of the hydraulic hybrids results in shorter payback than for electric systems. Hydraulic components are readily available mature products, while electric components for heavy duty vehicles are still in small volume production and have not yet achieved the maturity level of hydraulic components.

From a standpoint of near-term application, a simple hydraulic parallel system in pressure assist configuration is the most viable option, with all technologies readily available. Combined with a particulate filter, such a system could achieve up to 25 percent in fuel efficiency improvement, lower ozone-forming emissions, lower greenhouse gas emissions and low particulate levels at a cost premium lower than for a CNG or LNG engine.

Comparable energy efficiency can be achieved with an electric torque assist system at a similar cost premium but with better packaging capabilities, better controllability and improved noise characteristics. The electric system would not impose any weight penalty if a lighter engine and transmission were used. The electric option has a lot of potential for future improvement. Electric system component cost and quality are likely to improve to match hydraulic components. An electric system is feasible today and can be very competitive with the hydraulic option. In the longer term, the electric system may cost less than a hydraulic system.

An electric dual mode system would provide energy savings comparable to a parallel system, but at higher weight and cost. If emissions and noise were the driving factors, a series (dual mode) system would be commercially viable. The premium in that case could be covered by the user. It is a conceivable scenario. CARB estimates the cost of re-powering a conventional system to a cleaner technology to be an average of US$50,000 (including a particulate filter). The estimated cost of implementation is about US$1 per household per year. If this kind of incentive were available to hybrid technology, a dual mode system, optimized for fuel consumption, emissions and noise, could be developed and commercialized within two to three years.

REFERENCES

1 Gordon, D., Burdelski, J., Cannon, J.S., “Greening Garbage Trucks: New Technologies for Cleaner Air”, Executive Summary, INFORM 2004, www.informinc.org/fact_ggt.php

2 California Air Resources Board, “Enforcement of Regulation Curtailing Diesel Garbage Truck Emissions Begins”, News Release 23/02/2005, www.arb.ca.gov/newsrel/nr022305.htm

3 American Recycler, “Equipment Spotlight – Refuse Trucks”, April 2004 www.americanrecycler.com/apr03/04spotlight03.html

4 Clark, N.N., and Lyons, D.W., “Emissions from CNG and Diesel Refuse Haulers Using Six Engine Types in New York City”, Seventh CRC On-Road Vehicle Emissions Workshop, San Diego, April 1997, pp. 5-49 to 5-64

5 Dembski, N. et al., “Development of Refuse Vehicle Driving and Duty Cycles”, SAE Paper 2005-01-1165

6 Blohm, T., Anderson, S., “Hybrid Refuse Truck Study”, Virtual product Design Conference, Huntington Beach, CA, 2004

7 PVI, product information, www.pvi.biz

8 Renova, “Unique Swedish Refuse Vehicle Runs on Gas and Loads Using Electric Power”, Press Release, 26 November 2003, www.cleanowa.com/nyheter/pressrelease031126.pdf

9 Allison Transmission, www.allisontransmission.com/product/electricdrive/epsystem.jsp

10 BAE Systems, www.hybridrive.com

11 ISE Research, product information, www.isecorp.com/ise_products_services/diesel_hybrid_drive_system/

12 Azure Dynamics, www.azuredynamics.com

13 Enova, www.enovasystems.com

14 Oshkosh, www.oshkoshtruckcorporation.com

15 Hybrid Bus Technologies, LLC, “UQM Technologies Propulsion Systems and Generators Drive Hybrid Electric Transit Buses Delivered to Los Angeles International Airport”, www.uqm.com/press/news/05-18.html

16 EPA, “Hydraulic Hybrid Technology – A Proven Approach”, www.epa.gov/otaq/technology/420f04024.pdf

17 “Eaton and Peterbilt to Produce Hydraulic Hybrids”, Green Car Congress, 20 October 2004, www.greencarcongress.com/2004/10/eaton_and_peter.html

18 Dana Corporation, “Dana Corporation Signs Agreement with Permo-Drive Technologies to Commercialize Fuel-Saving Hybrid-Hydraulic Technology for Refuse Industry”, Press Release, 9 September 2005, dana.mediaroom.com/index.php/press_releases/2005

19 Matheson, P., Stecki, J., “Development and Simulation of a Hydraulic-Hybrid Powertrain for Use in Commercial Heavy Vehicles”, SAE Paper 2003-01-3370, 2003 SAE International Truck and Bus Meeting and Exhibition, 10-12 November 2003

20 AQMD Board Meeting, Agenda No. 3, 9 July 2004, www.aqmd.gov/hb/2004/04073a.html
21 Fiba Canning, www.fibacanning.com/cumulo/hybrid.htm
22 Reckhorn, T., Dietz, A., Mueller, K.H., "Drive Systems for Electric, Hybrid and Fuel Cell Vehicles", Proceedings of 18th Electric Vehicle Symposium, EVS-18, Berlin, 2001
23 Sauer Danfoss, "Series 90 Axial Piston Pumps", product information, www.sauerdanfoss.com
24 Kopecky, C., "Ultracaps Take the Bus", EPCOS Components Magazine, Issue 1, January 2001, www.epcos.com
25 Eaton Corporation, "Heavy Duty Hydrostatic Transmission", product information, www.eaton.com
26 Hydac, product information, www.hydac.com
27 Allison Transmissions, product information
28 Cummins Corporation, product information
29 Maxwell Technologies, Inc., product information, www.maxwell.com
30 NESSCAP Co., Ltd., product information, www.nesscap.com
31 Costow, T., "Large Ultracapacitors Aim at Hybrids", Automotive Engineering International, August 2005, pp. 45-46, www.automotiveengineeringintlmagazine.sae.org/automag/electronics/08-2005/1-113-8-42.pdf
32 U.S. Department of Energy, "Gasoline and Diesel Fuel Update", http://tonto.eia.doe.gov/oog/info/gdu/gasdiesel.asp
33 California Air Resources Board, "Waste Collection Vehicle Regulation", www.arb.ca.gov/diesel/factsheets/trashtruck.pdf
34 Chandler, K., Norton, P., Clark, N., "Waste Management's LNG Truck Fleet: Final Results", DOE Report, January 2001, www.eere.energy.gov/afdc/pdfs/WasteLNGfinal.pdf

Appendix A – Simulation Model Diagrams

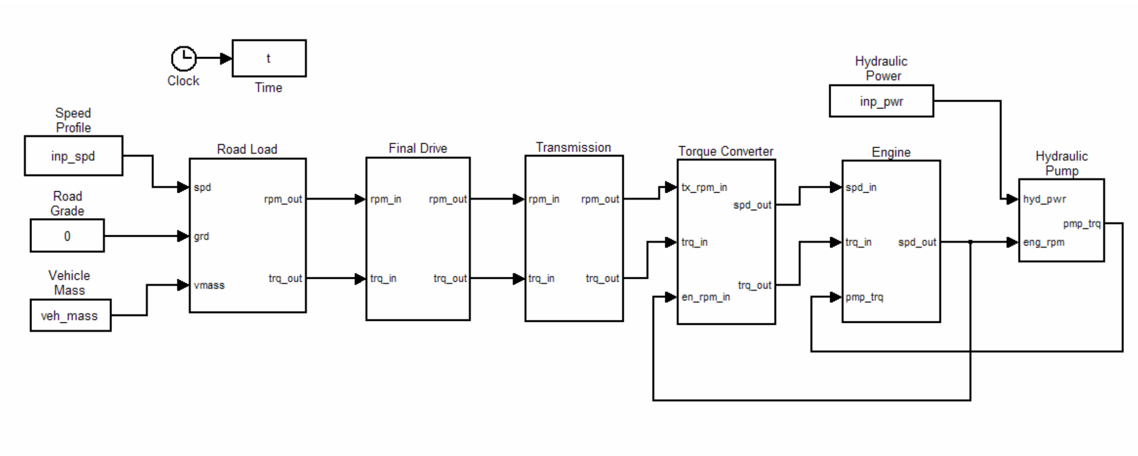

Figure A-1: Conventional Refuse Truck Powertrain Model

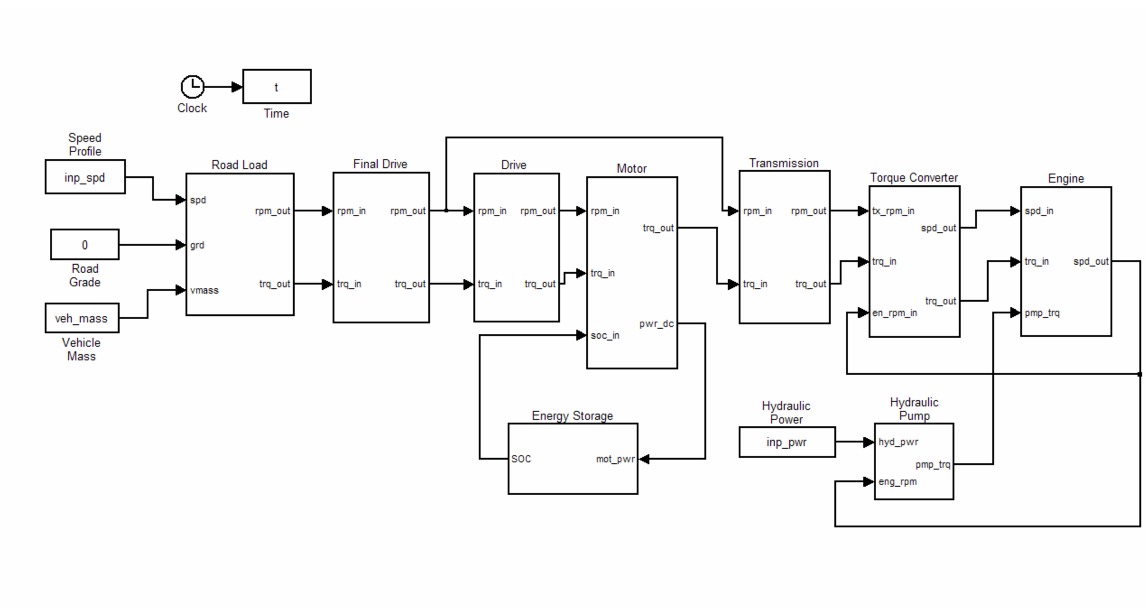

Figure A-2: Electric Parallel Hybrid Powertrain Model – Torque Assist

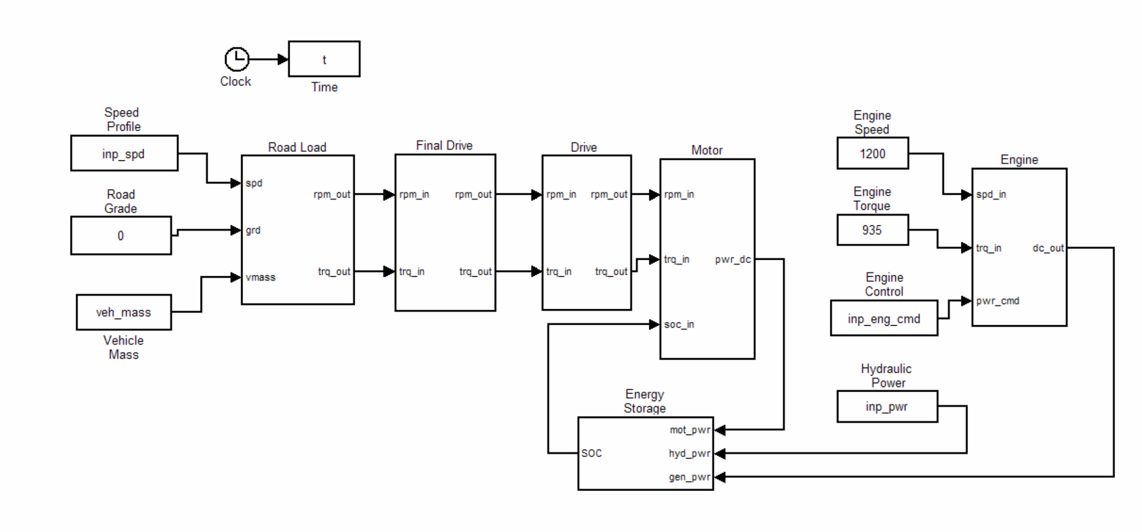

Figure A-3: Electric Dual Mode Hybrid Powertrain Model

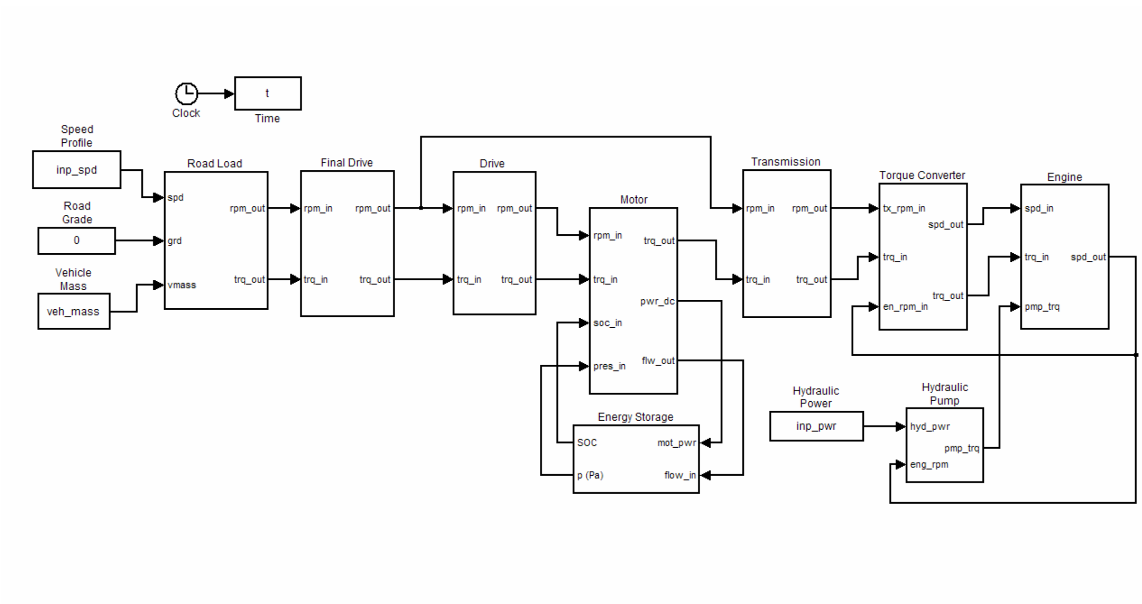

Figure A-4: Hydraulic Parallel Hybrid Powertrain Model – Torque Assist

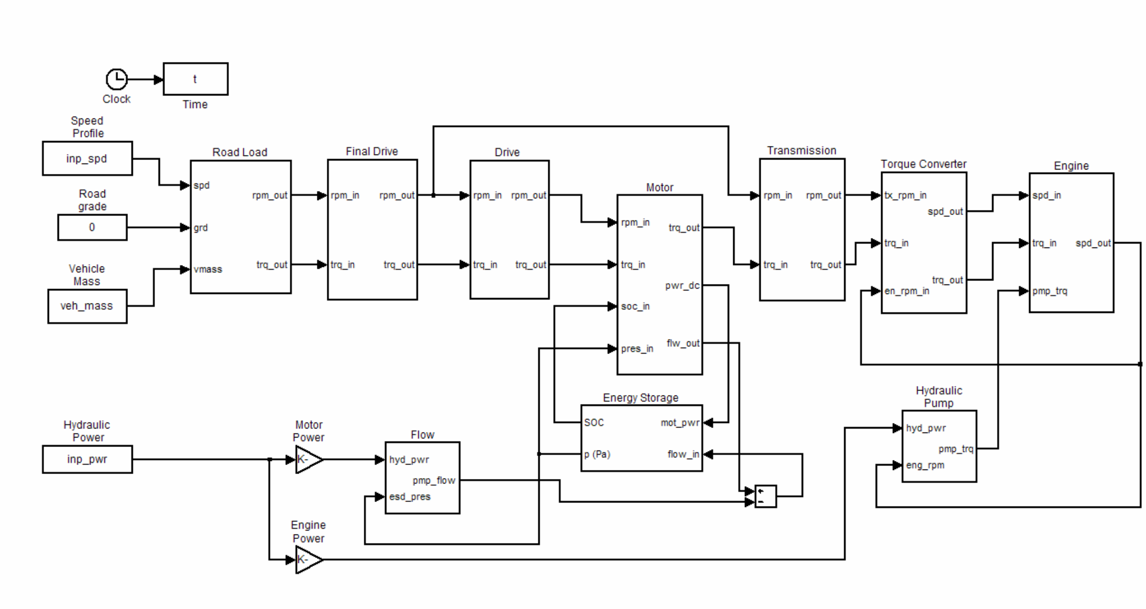

Figure A-5: Hydraulic Parallel Hybrid Powertrain Model – Pressure Assist

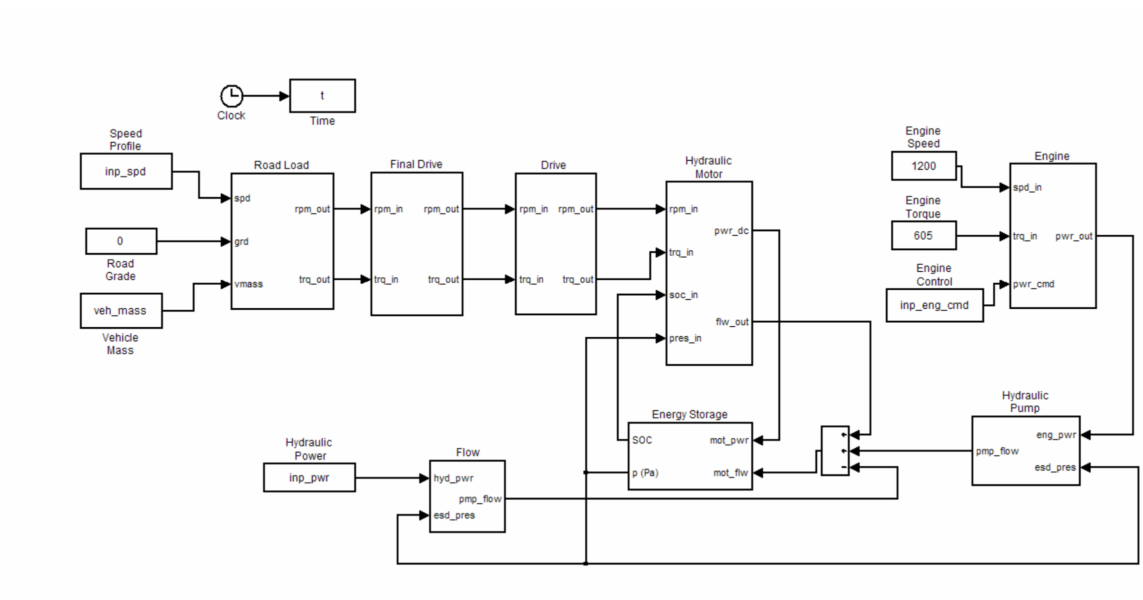

Figure A-6: Hydraulic Dual Mode Hybrid Powertrain Model