

# **Hybrid Diesel Electric Bus Technology and Feasibility Study**

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## **ABSTRACT**

**Performance and fuel consumption tests were conducted to quantify the differences between two model year 2001 hybrid diesel-electric drive configurations against a model year 2004 conventional diesel (New Flyer Invero). The engines installed in all three buses were Cummins ISL/B featuring 4.0 gram NO<sub>x</sub> technology.**

**The buses were loaded to their maximum gross weight rating. Fuel consumption tests were conducted on actual City of Ottawa (OC Transpo) routes and performance tests were conducted on City of Ottawa roads in and around NRC's Centre for Surface Transportation Technology's (CSTT) Uplands campus.**

**The testing was complemented by an analysis of projected life cycle costs, based on data supplied by bus/powertrain manufacturers, transit authorities already operating hybrid buses, NRC test results and OC Transpo's existing fleet of conventional diesel buses. The life cycle trends are presented in this paper, however, the exact dollar figures have been excluded due to the rather high degree of uncertainty with hybrid component parts.**

**Emissions tests were not performed as part of this program, however, historical data were acquired and used to better understand the potential greenhouse gas emission reductions.**

**The results of the performance and fuel consumption tests are presented below.**

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## 1 INTRODUCTION

The Hybrid Diesel Electric Bus Feasibility Study was contracted by the City of Ottawa, in the fall of 2004, to the National Research Council's Centre for Surface Transportation Technology (CSTT). The study was funded with assistance from the Green Municipal Enabling Fund, a Fund financed by the Government of Canada and administered by the Federation of Canadian Municipalities. CSTT provided an independent third-party evaluation of two commercially-available hybrid bus systems, under winter conditions, for service on the Ottawa transit system network, which includes bus rapid transit in addition to congested inner city routes.

CSTT developed comprehensive performance tests and a simulated revenue service trial to assess the operating characteristics of two diesel-electric hybrid drive systems under consideration, and to compare these against an existing City of Ottawa conventional diesel transit bus.

The scope of the study also included a projection of the life cycle cost of each hybrid technology over the expected 18-year life of the bus. This included the initial capital costs, infrastructure costs and maintenance and operating costs. Data used in this portion of the study were drawn directly from City of Ottawa operations (OC Transpo) and fleet maintenance data bases, and from transit operations in New York City and King County (Seattle). Further data used in this portion of the study were provided by the hybrid OEMs about their respective hybrid drive systems. The financial results of the life cycle costing are not presented in this paper.

Although it is beyond the scope of this paper to fully explain the internal differences between a series and parallel hybrid drive, Figures 1 and 2 illustrate the power distribution in the two systems. The series drive utilizes a bank of 46 lead acid automotive batteries whereas the parallel drive employs two Nickel Metal Hydride batteries for energy storage.

At the request of the two hybrid drive manufacturers, all of the figures shown below illustrate one hybrid configuration against a diesel bus and not parallel hybrid versus series hybrid.

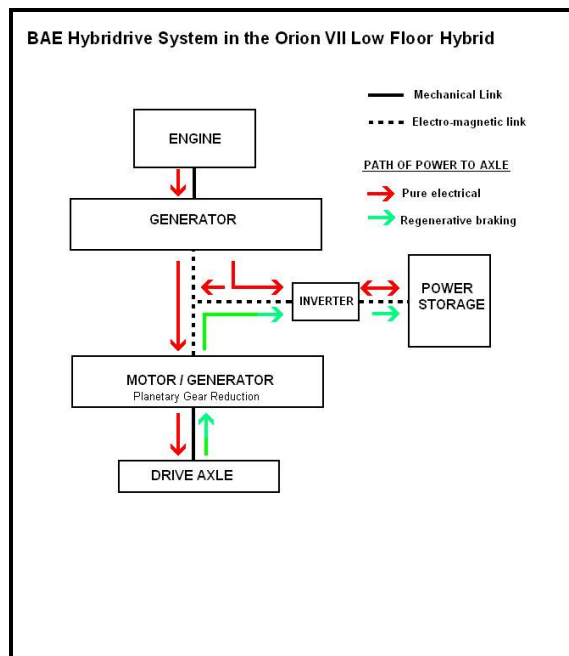


Figure 1 - Series drive layout

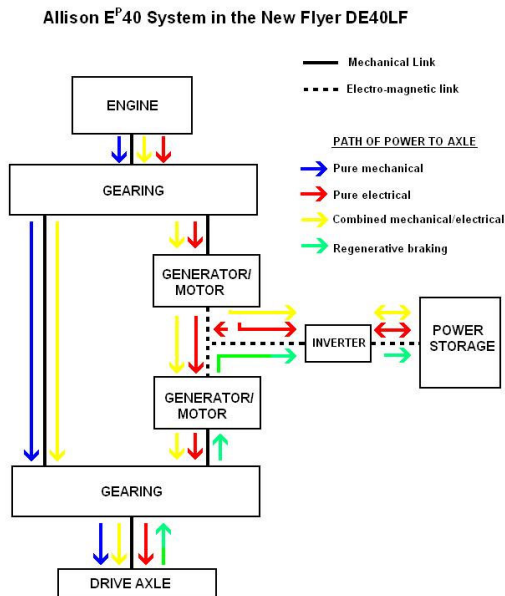


Figure 2 - Parallel drive layout

## 2 EMISSIONS TESTING

Emission testing was not carried out as part of this study primarily because the diesel engines used in the hybrid buses for the current study did not represent the latest diesel engine technology, which is expected to change again in 2007 to meet more stringent emissions requirements, known to be coming. As well, emissions and fuel economy test data, already gathered by the Emissions Research and Measurements Division of Environment Canada and used in this study, is representative of the diesel-electric hybrid buses evaluated here and of the relative effect of hybridization on tailpipe emissions. The Environment Canada testing employed a heavy-duty chassis dynamometer and incorporated dilution tunnel technology for sampling and measuring

vehicle exhaust, and was performed in accordance with SAE protocol J2711. The results of these tests are available in the public domain.

### 3 PERFORMANCE RESULTS

Both hybrid buses and the conventional diesel were subjected to the following performance tests:

**Fuel consumption;  
0-80 km/h acceleration;  
Regenerative braking coastdowns;  
Acceleration up a steep hill;  
Regenerative braking down a steep hill;  
Sound testing (interior and exterior).**

#### 3.1 Fuel consumption

All three buses were driven over actual city of Ottawa routes, following a lead diesel bus, performing revenue service. The fuel consumption of all three buses was monitored and calculated for each of the routes. Both hybrid systems achieved fuel economy improvements estimated at between 17% to 26% when deployed in high stop density and low speed routes and most peak service routes. Comparable percentage reductions in greenhouse gas emissions can be expected on these same kinds of routes. Figures 3 and 4 illustrate the fuel savings.

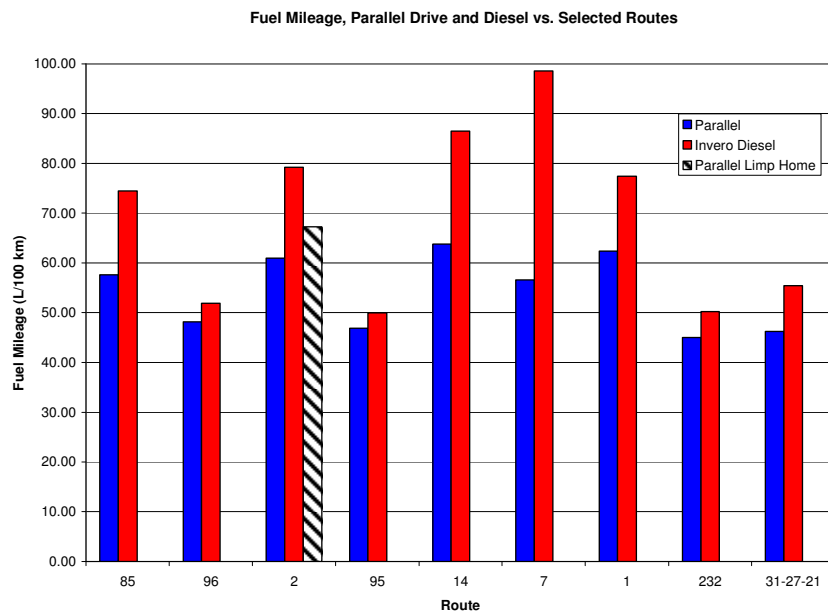


Figure 3 - Fuel Mileage of Parallel Hybrid vs. Conventional Diesel

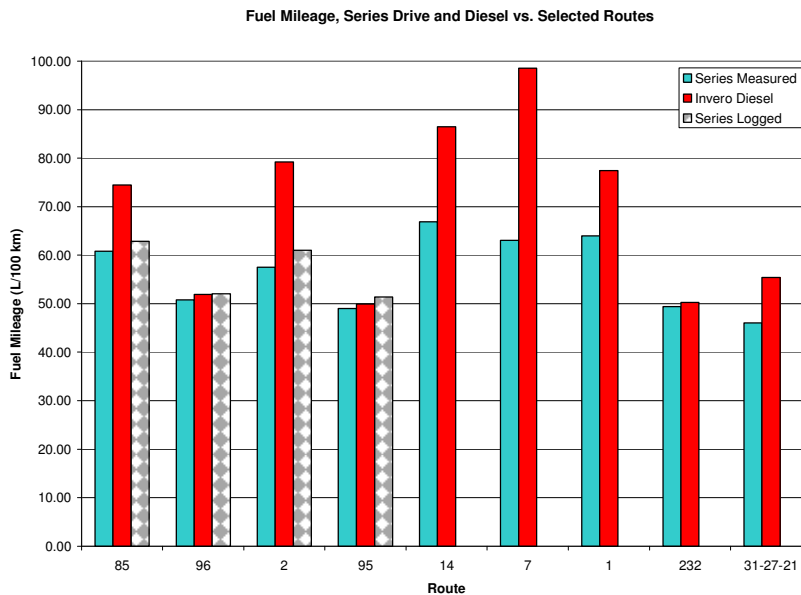


Figure 4 - Fuel Mileage for Series Hybrid vs. Conventional diesel

**Based on the results of the fuel consumption testing, CSTT has calculated that carbon dioxide emissions will be reduced from 29 to 44 tonnes per year for every hybrid bus introduced on high stop density and low speed routes in Ottawa.**

**Neither of the hybrid systems evaluated in this study provided significant fuel savings on low-stop frequency and high-speed routes, such as test routes #95, 96 or rural express route 232. See Figures 3 and 4.**

**While reviewing the data it became clear that the percentage fuel savings offered by hybrid buses over diesel can be directly linked to the number of stops per kilometer. CSTT has plotted the fuel economy savings for each of the buses against the number of stops per kilometer for each test route and has generated the graph at Figure 5. A line of best fit was generated for each of the curves with associated  $R^2$  value of 0.87. This linear formula was then used to generate a route-wise percentage reduction in fuel consumption, against conventional diesel, based on the stop density. It is clear that routes with stop densities greater than 5 stops/km should realize significant fuel consumption savings (with a corresponding reduction in greenhouse gas emissions).**

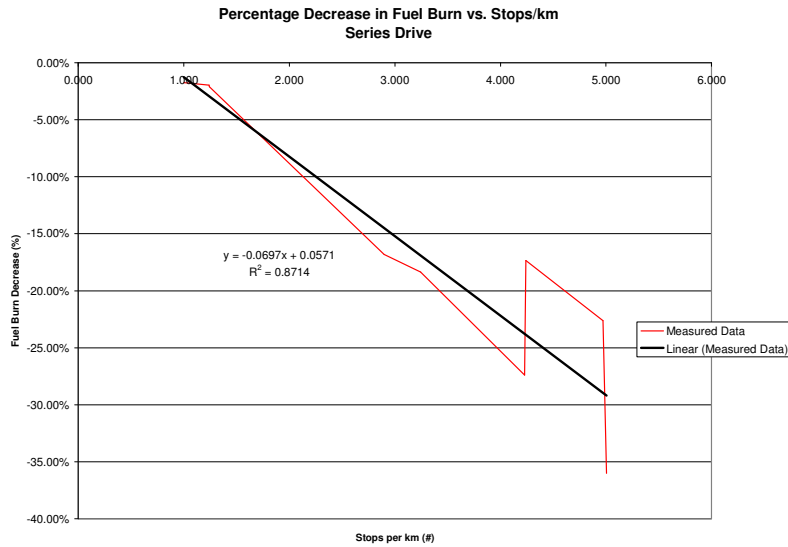


Figure 5 - Relationship between stop density and fuel savings (series hybrid)

### 3.2 0-80 km/h Acceleration Tests

The buses were stopped at a pre-determined area and the driver attempted to reach 80 km/h, on flat and level terrain, as quickly as possible. The tests were performed on days with light or no wind and clear and dry road conditions. The results indicated that both hybrid buses enjoyed a distinct advantage over conventional diesel from 0-40 km/h (See Figure 6 for parallel drive results). However, as speed increased, the percent difference narrowed. In fact, the series hybrid bus took longer to reach 80 km/h than the conventional diesel.

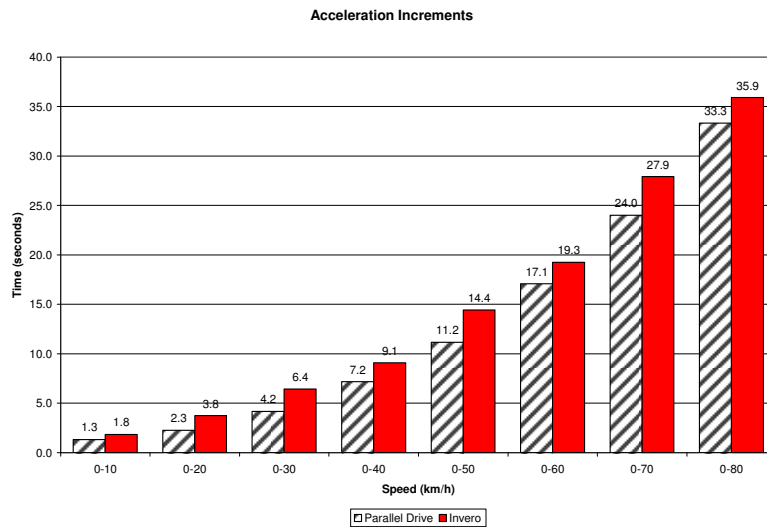


Figure 6 - Results of 0-80 acceleration tests (parallel drive vs. Invero diesel)

### 3.3 Regenerative Braking Coastdowns

In order to measure the effectiveness of the regenerative braking of the hybrid buses, a set of coastdown tests were performed. The coastdown tests were not intended to replicate any typical in-service characteristic of a city bus. Rather, the tests were conducted to remove any input from the foundation brakes and isolate the contribution of the regenerative braking system. Note: the series drive employs five distinct brake maps which vary the amount of regenerative intervention with 1

being the lightest and 5 being the heaviest. The driver was asked to cruise at 80 km/h and then take his feet off both pedals at a prescribed start line. The bus then coasted to 0 km/h, stopping only by means of aerodynamic drag, rolling resistance and the regenerative braking. The distance and time from 80 km/h to 0 km/h were recorded. In general the conventional diesel bus required nearly three times as much time to decelerate than the series drive hybrid. See Figure 7.

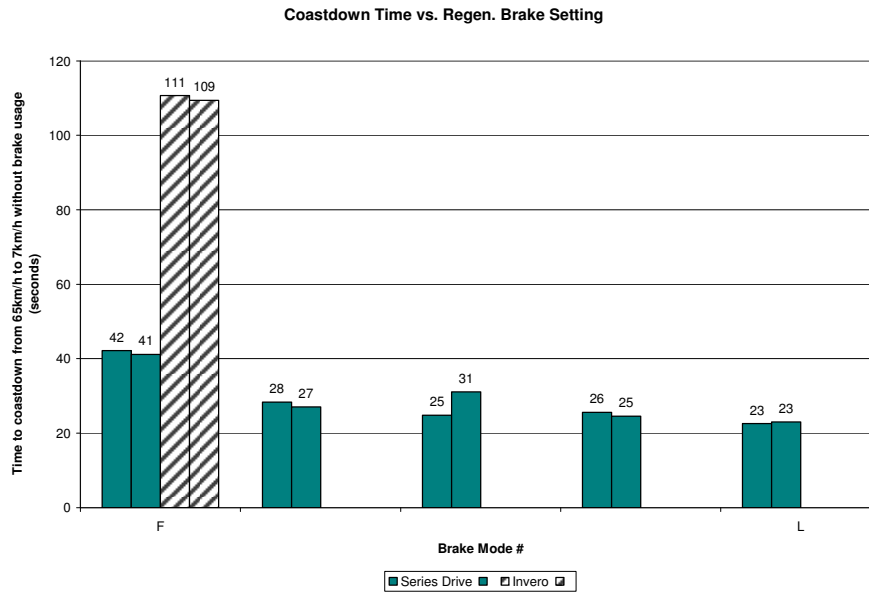


Figure 7 - Results of coastdown tests (series drive only)

### 3.4 Acceleration up a steep hill

Since hybrid buses employ diesel engines and electric motors it was of interest to determine if they could accelerate up a hill faster than a conventional diesel. Each of the buses was stopped at the base of a hill and the driver was asked to accelerate up the hill as quickly as possible. The conventional diesel was driven in transmission selection '3' in order to minimize gear hunting. Both the hybrids employed continuously variable transmissions (CVT) and were simply placed in 'D'. The results showed that the hybrid buses were only marginally faster with respect to hill climbing than their conventional diesel counterpart. See Figure 8.

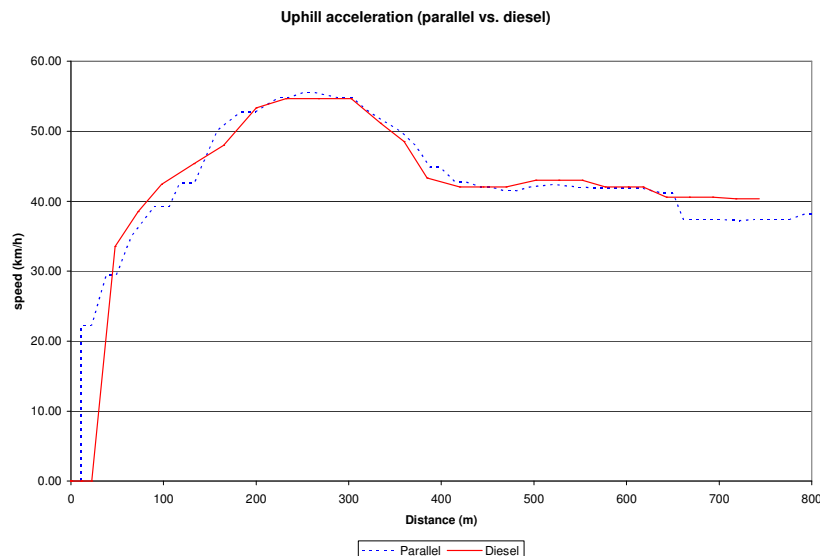


Figure 8 - Results of hill climbing tests (parallel vs. diesel)

### 3.5 Regenerative Braking Down a Steep Hill

In order to test the effectiveness of the regenerative braking with respect to halting a bus' progress down a hill, a series of steep downhill tests were performed. A string pot linear displacement transducer was mounted between the brake pedal and the floor of the bus to measure the amount of brake pedal travel. The bus driver was instructed to drive down a steep hill, maintaining a speed of 50 km/h. He was instructed to use the pedals, at his discretion, in order to maintain that speed. The test engineer monitored the forward speed and called for brake, or accelerator, input as required. The results of the tests indicate that a properly tuned hybrid bus can greatly reduce the amount of service brake use when descending hills. Since the amount of regenerative energy varies, based on the battery state of charge, so too does the amount of regenerative braking. However, in general, the hybrid bus required 20% to 60% fewer brake applications when compared to conventional diesel. This should significantly reduce the number of times each bus will require brake service, particularly for those buses servicing hilly terrain. See Figure 9.

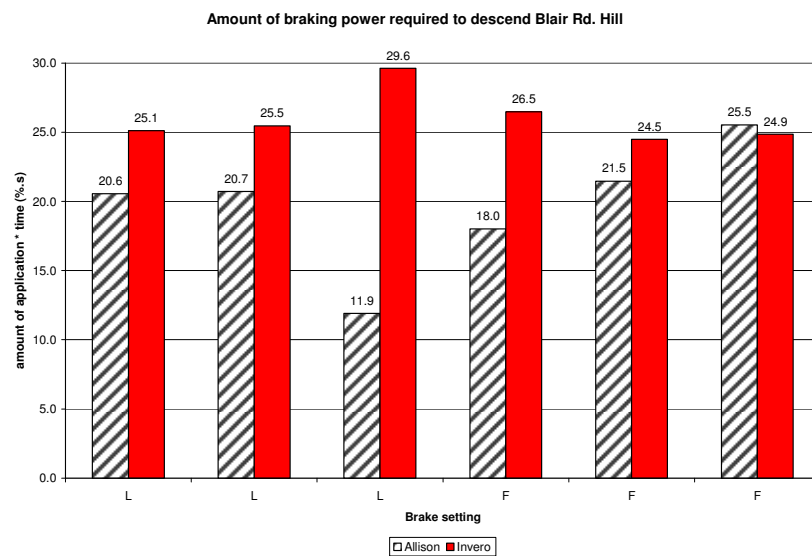


Figure 9 - Amount of service brake used down a steep grade

### 3.6 Emissions Testing

Emissions testing of similar hybrid diesel-electric buses at Environment Canada indicate that significant emission reductions will be realized as a direct result of hybridization of diesel buses, which will be in addition to expected reductions resulting from improvements in diesel engine technology.

Results from Environment Canada's Central Business District (CBD) testing indicated that reductions in fuel consumption and carbon dioxide emissions of up to about 30% could be expected with the introduction of hybrid buses on City stop-and-go routes, which is in good agreement with the actual fuel consumption testing completed during this study. Similarly, reductions in regulated tailpipe emissions, as a result of hybridization, of up to 90% for carbon monoxide and unburned hydrocarbons, and up to 30% for oxides of nitrogen and 60% for particulate matter, would be expected on the slow speed, inner-city routes [1], [2].



### 3.7 Sound Testing

The hybrid buses were measured to be slightly quieter than conventional diesel buses on the interior during hard accelerations, however, there were no significant differences in exterior noise levels among any of the buses evaluated in this study. At cruise speed, both conventional and hybrid buses are relying on their diesel engine for propulsion, therefore it stands to reason that the sound data for cruising was comparable. See Figure 10.

<i>Climate Control ON</i>	<i>Driver's Seat (dBA)</i>		
	Hybrid		Diesel
<b>Low Idle</b>	<b>63.4</b>		<b>60.9</b>
<b>High Idle</b>	<b>63.6</b>		<b>61.3</b>
<b>Acceleration 0-70 km/h</b>	<b>80.3</b>		<b>84.5</b>
<b>Cruise @ 70 km/h</b>	<b>66.7</b>		<b>55.4</b>
<i>Climate Control ON</i>	<i>Rear Bench Seat (dBA)</i>		
	Hybrid		Diesel
<b>Low Idle</b>	<b>59.5</b>		<b>57.7</b>
<b>High Idle</b>	<b>61.3</b>		<b>61.3</b>
<b>Acceleration 0-70 km/h</b>	<b>83.8</b>		<b>84.6</b>
<b>Cruise @ 70 km/h</b>	<b>70.1</b>		<b>68.0</b>
<i>Climate Control OFF</i>	<i>Driver's Seat (dBA)</i>		
	Hybrid		Diesel
<b>Low Idle</b>	<b>50.3</b>		<b>45.3</b>
<b>High Idle</b>	<b>48.3</b>		<b>47.2</b>
<b>Acceleration 0-70 km/h</b>	<b>78.9</b>		<b>83.6</b>
<b>Cruise @ 70 km/h</b>	<b>64.6</b>		<b>63.4</b>
<i>Climate Control OFF</i>	<i>Rear Bench Seat (dBA)</i>		
	Hybrid		Diesel
<b>Low Idle</b>	<b>56.8</b>		<b>54.4</b>
<b>High Idle</b>	<b>59.8</b>		<b>60.2</b>
<b>Acceleration 0-70 km/h</b>	<b>83.5</b>		<b>85.2</b>
<b>Cruise @ 70 km/h</b>	<b>70.1</b>		<b>66.6</b>

Figure 10 – Results of sound testing

## 4 LIFE CYCLE COSTS

The life cycle cost analysis of the hybrid systems is characterized by a relatively high degree of uncertainty, because of a sparse amount of real, in-service data due to limited operating experience with these systems, to date. This is a common limitation in the evaluation of new

technologies. The available data show that the life cycle costs of the two hybrid systems will be similar to each other.

The results of the life cycle cost analysis indicate that the additional costs associated with the introduction of hybrid buses will be offset, primarily because of improved fuel economy. Other factors that were not considered in this study, such as reduced engine and brake maintenance costs (resulting from reduced engine loading and regenerative braking), possible future increases in the price of diesel fuel, and new or different government subsidies, would reduce the life cycle costs of hybrid buses from those projected in this report even further, thereby making the conversion to a hybrid fleet even more cost-effective.

## 5 HEAVY VEHICLE WEIGHTS AND DIMENSIONS

For the purposes of testing, each of the test buses was loaded to its manufacturer's printed gross vehicle weight rating. However, this resulted in all three test buses' rear axles being overloaded, when compared to current Ministry of Transportation of Ontario (MTO) regulations. CSTT developed a simulation which illustrated that the rear axles of all three current generation test buses will be overloaded under many passenger loading conditions. The added weight of hybrid components does not significantly add to this overload when compared to diesel buses of the same vintage (e.g. Invero). The overload was quite dramatic when compared to diesel buses of the late 1970s and early 1980s. The exterior and interior dimensions of the bus were essentially the same as their diesel powered counterparts with the exception of overall height. The hybrids were roughly six inches higher than a conventional bus with roof mounted air conditioning.

Since the center of gravity of most low floor hybrid buses is higher than diesel buses it was of interest to determine the roll threshold of the hybrid buses. In addition to static modeling, a tilt test was performed on the series hybrid bus and the conventional diesel to determine if the hybrid's roll threshold was significantly lower than that of a conventional diesel. The conventional diesel bus' wheels lifted off the table at 34.4 degrees whereas the series drive, with its 4,000 lbs of roof mounted batteries, lifted at 28.8 degrees See Figure 11. Given the nature of urban transit, CSTT does not feel that this degradation in roll threshold will negatively affect the performance of the buses. It is unlikely that a city bus could achieve the necessary lateral accelerations to roll over, unless the roll over was tripped via an embankment or a curb.



Figure 11 - Series drive hybrid bus on tilt table

## 6 CONCLUSIONS

If hybrid buses are deployed on high stop density routes, both the series and parallel propulsion units will meet the performance requirements stipulated by the City of Ottawa. The parallel hybrid system achieved slightly better performance results based on a series of tests performed on model year 2001 hybrid buses. Additionally, the parallel propulsion system employs a lighter energy storage system, displayed lower fuel consumption (albeit statistically not significant), has lower predicted life cycle costs (based on limited historical data from other hybrid users) and it does not require an external battery conditioning system.

If transit authorities wish to realize the savings touted by the hybrid manufacturers, it is imperative that hybrid buses be targeted to specific routes with a high stop density and low average speed. Failure to do so will negate much of the potential financial and greenhouse gas emissions savings.

Currently, there are no significant differences in interior or exterior noise signatures between hybrid buses and conventional buses. Components such as air compressors and air conditioning packs are still major contributors to noise, and are found on all buses, regardless of propulsion system.

With the exception of 0-40 km/h acceleration times and regenerative braking, most other performance measure results were similar, when comparing hybrids to diesel buses. It is not likely that drivers will notice significant changes when the new technology becomes commonly available.

## 7 REFERENCES

- 8 [1] ORION VII TRANSIT BUS EQUIPPED WITH BAE HYBRIDRIVE PROPULSION SYSTEM (MY2004): EMISSIONS AND FUEL ECONOMY TEST REPORT, REPORT #04-18, SEPTEMBER 2004; MEYER AND RIDEOUT.
- 9 [2] SOUTHEASTERN PENNSYLVANIA TRANSIT AUTHORITY DIESEL ELECTRIC BUS EVALUATION; REGULATED EMISSIONS AND FUEL ECONOMY, REPORT #03-38, DECEMBER 2003; MEYER AND RIDEOUT.