Hybrid Transit Bus with Optimized Energy Requirements

Alan Ponsford, Director, Newbus Technology Ltd
Mike Kellaway, Director, Newbus Technology Ltd

Abstract

The target of this Newbus Technology study was to configure an optimum specification for a low energy, 40 foot hybrid transit bus. To facilitate this, a baseline hybrid design was used to identify the primary loss mechanisms, together with their relative importance, when in operation during actual intensive city duty. This used an ADVISOR model operated though real world, logged drive cycles. The second stage was to investigate the design sensitivity of these various loss mechanisms, in terms of each sub-system, when calculated against changes in vehicle fuel consumption and overall system efficiency. By running the simulations, and varying the individual sub-system losses across a range, the overall sensitivity could be calculated. The third technical section was then to adjust the generic sub-system performances to practical, near future solutions. This optimized bus was then simulated over both real duty cycles and also idealized simplified drive cycles. The summarized findings outline the significant improvements achieved. These showed a 55% increase in fuel mileage using the latest hybrid powertrain technology. When combined with advanced vehicle engineering, this increase was 113% over the baseline hybrid. The commercial considerations outline an overall approach for a commercially viable, low energy hybrid bus product suitable for US operation.

Keywords: Bus, hybrid, heavy duty, optimization

1. Introduction

This study set out to deliver a rigorous evaluation of hybrid transit bus design optimisations. The underlying premise was that current and future changes in energy and powertrain costs will be design drivers for changes in transit bus design. The most viable solutions will require changes to the overall system, and the various sub-systems, to create a satisfactory product. This product profile needs to meet a new combination of requirements.

These requirements include:
- acceptable performance for both the operator, driver and passenger
- viable cost basis covering project development, initial purchase and in-service operation,
- environmental behavior to suit both the local and global emission standards.

Recent studies confirm that transportation is the fastest growing sector, in terms of increasing energy use, in most nations. Other contemporary studies, typified by the 2002 APTA report [1], show the very significant potential gains that can be achieved with a partial, albeit limited, switch from private to public transport modes.

The city environment appears to be the most attractive sector for such modal changes from personal to collective transport. These changes offer benefits from reduced congestion, increased average journey speeds plus an improvement in local air quality. The last feature serves to benefit travelers, pedestrians and all city dwellers. Any reduction in fuel use will benefit the national situation regarding total energy requirements. The work covered here has studied how improved bus designs, and bus services, could help achieve these aims.

2. Scope

This Newbus paper covers a research program of design optimization of a hybrid transit bus, based on a combination of simulated and real world data. The significant majority of the work has used ADVISOR simulation to evaluate the very many variables within the vehicle design. However, this research program is an extension of earlier work that combined vehicle system modeling with actual benchmarked data from buses in regular operating service. This Newbus paper was presented at the NREL ADVISOR User Conference, Costa Mesa, August 2000 [2].

The latest work has analyzed a typical bus application for intensive, city operation. By initially focussing on one configuration, the fundamental energy and power ratings were established. The work was then extended to cover the design sensitivities of the various sub-system energy consumers. This output was finally compiled into an optimum bus design, using the current best practice solutions for the overall vehicle. This included new approaches to certain fundamental issues that impact both the technical and commercial profile of the new design.

It is recognized that the program of work is close in content to that covered in the 21st Century Truck Program [3]. This work showed the possible improvement in fuel mileage of 260% over a base line diesel mechanical bus. It set the target at a 300% gain over baseline. It was decided to use this same fuel mileage approach, rather than the alternative fuel saving, in this paper for this reason. With the work covered here, certain differences exist in the survey of factors including drive cycles, passenger loadings and A/C systems when compared to the 21st Century study. The required matching design work of the advanced optimum bus has also been progressed to deliver these simulated benefits in near-future bus products.

The units used within the simulation studies are metric, but overall fuel consumption are in miles-per-gallon, using US gallons since these make a familiar output for most readers. Conversion values are included below for the results in miles-per-gallon (Imp) and the metric equivalent in litres/100km.

3. Vehicles and their specifications

3.1 Baseline vehicle

The approach used was to cover the baseline design performance and then look into effects of independent changes of each sub-system. The baseline design uses 40 foot heavy-duty hybrid bus suitable for intensive transit or city operation within North America. This model incorporates the various powertrain aspects plus the related vehicle losses and auxiliary system efficiencies. The nominal curb weight was set at 13,880kg (30,600lb) using the baseline system values for diesel engine, battery pack etc. It was decided to evaluate the worst case operating case, that of crush laden. Generally, studies for bus simulation are run at either half seated load or half maximum passenger load. Practical experience inevitably shows the worst problems when the buses, and their systems, are running at maximum or overloaded conditions.

It was therefore decided to carry out the study is based on reference maximum payload of 90 passengers. This equates to a ‘cargo mass’ of 6,120kg (13,490lb) to European ECE R 36 regulations. This is very close to the 6,125kg (13,500lb) using the US APTA White Book specifications as both use a similar 68kg or 150lb passenger respectively. This approach led to maximum laden weights around 20 tonnes or 44,000lbs GVWR set by the technical limits of axle and tire capacity. This puts the critical bus design parameter of Passenger Fraction percentage (%PF) of GVWR to just above 30%. In the studies below, the passenger numbers – the actual 'pay' load – is kept constant and the vehicle mass adjusted as required.

The powertrain comprised a 125kW de-speeded diesel plus generator system. The engine was operated below 2,000rpm to improve fuel efficiency. The fuel map best zone was at 205g/kWh, around 41% thermal efficiency. The motor was continuously rated at 175kW. Both motor and generator were of the AC induction type. The battery pack was lead acid of a nominal capacity of 45kWh.

The maximum speed and grade limits were set at 67mph and 19% respectively. The powertrain and energy storage ratings are set to match the industry performance standards. These include the APTA White Book requirements for acceleration and speed on grade.

3.2 Design variations

A range of analyses were carried out looking at various options for engine, battery, drives etc. To avoid a limitless number of possible combinations, the various design selections were pulled into two main packages. On the hybrid powertrain, the improvements in efficiency covered the diesel engine, the electrical machines, battery pack and transmission. This optimized combination was termed the **Advanced Hybrid** powertain.

The studies into the automotive engineering looked at the vehicle features outside of the core powertrain. These covered the bus shell, the running gear and the assorted auxiliary systems such as cooling, steering and braking. This package of changes to the base vehicle were grouped under the heading **Advanced Vehicle** configuration.

The final build option included the air-conditioning or A/C system. This important aspect is essentially divorced, in terms of its power consumption, from both the powertrain and vehicle systems. It is dominated by ambient conditions, including the effects of geography and season, plus passenger loadings. It was decided therefore to run the A/C hotel power study separate from the main powertrain and vehicle work. In this way, the very significant maximum A/C loads would not mask the other developments.

3.3 Model matrix

The combination of the above designs led to a matrix of ADVISOR simulation models. The summary of their specification is as follows:

Table 1: Model designations and major features

Model	Vehicle	Powertrain	A/C
NBUS_01	Standard	Standard	No
NBUS_02	Standard	Advanced	No
NBUS_03	Advanced	Advanced	No
NBUS_04	Standard	Advanced	Yes
NBUS_05	Advanced	Advanced	Yes

The further details of these design variations, together with their various systems, are described below.

3.4 Drive cycle

The selected drive cycle will be unfamiliar to most of the US market as it is based on an intensive city bus cycle measured in London, UK. This is termed the Millbrook London Transport Bus cycle, or

CYC_MLTB in ADVISOR speak. This MLTB cycle was used for a number of reasons. It was intended to use a real world cycle that had been established and checked against logged data. The MLTB background data also includes cycles measured across a range of passenger loadings and traffic conditions. This represented a useful slow speed cycle in congested city traffic. The past simulation work carried out by Newbus Technology had also used this cycle looking at smaller 30 to 35 foot bus designs. By maintaining this drive cycle, it was therefore possible to study a large bus design that could, due to its high GVWR, be applied to double deck or articulated buses.

To ensure the validity of the MLTB results, a range of other cycles were checked. Another new cycle option is the SORT (Standardised On-Road Test) cycles developed by the UITP (Union International Transport Public). These have been developed to cover the modes of Heavy Urban, Easy Urban and Suburban and are termed SORT1, SORT2 and SORT3.

A last duty cycle option was an idealized cycle designed to reproduce the MLTB cycle overall operating 'deliverables' in terms of overall distance and time, number of stops and dwell period but optimising the velocity-time profile within these. This was reviewed to see the benefits of controlled running that might by available in precincts or on BRT-style bus-ways. This was called CYC_NBUS01.

3.5 Passenger loading

The final aspect relating to operating conditions was passenger loading. Runs were completed at a full range of passenger load factors to establish the effect on fuel consumption.

4. Systems and loss mechanisms

The design study process covered here uses the familiar major systems with their associated loss mechanisms. The usual main design factors that have been addressed include:

- diesel engine and its thermal efficiency,
- generator and related controller efficiency maps,
- motor and related controller efficiency maps,
- energy storage system including battery system losses,
- transmission effects,
- vehicle tare mass, combining glider and major units,
- auxiliary system energies, including cooling fan, power steering, compressed air, HVAC,
- tire and other rolling losses,
- aerodynamic specific resistance,
- vehicle controller and operating strategy.

4.1 Diesel

The baseline unit achieved 205g/kWh at maximum efficiency. This corresponds close to 41% thermal efficiency. The map covered the table of specific fuel consumption across the speed and torque ranges.

4.2 Generator

The generator was configured as an AC induction machine. The efficiency was set to a constant value as the minimum idling speed for the diesel avoided the low speed, low efficiency zones. This generator was a machine of relatively small diameter and low maximum torque rating. This unit was similar to those derived from the industrial machine volume base. It was directly connected to the engine output so its rotational speed was the same as the diesel.

4.3 Motor

The motor type used an AC induction machine with a tail mounted reduction gearbox using an epicyclic geartrain. The efficiency map was scanned over the whole speed range and against full forward and reverse torques. The motor used a maximum rated speed of 10,000rpm. It was combined with the reduction gearbox with a ratio of 4.0:1.

4.4 ESS

Baseline battery system used lead acid units. These had a somewhat higher mass than ideal to give sufficient power rating, particularly in regen mode, at an acceptable life.

4.5 Transmission

The final drive was set to 4.0:1 reduction to deliver a maximum speed in the 65 to 70mph band. The runs established a value of 67mph for the baseline design.

4.6 Mass

The baseline design, as described above, has an approximate 30% PF calculated from the 90 passenger mass expressed as % of GVWR mass. This used the glider plus powertrain masses for the unladen value.

4.7 Auxiliary systems

The standard auxiliary losses are related to power steering, air compressor and the two cooling fan drives. The alternator was included within the net engine value. The body and basic H+V loads were therefore covered in this manner, but only included the basic body loads – wipers, lights and blowers – and did not include A/C loads. The steering, compressor and cooling fan loads were taken from actual duty cycles. These used a profile of load against % occurrence to establish the mean running value.

A separate Newbus thermal study had addressed the issue of the two cooling circuits. The 'hot' circuit covered the diesel and electrical energy dump unit, whilst the 'cool' circuit covered the electrical units including the controllers. This second circuit, although low in heat rejection, demanded special study on optimizing the flow rate, fan and radiator design.

4.8 Tire

The standard tire was set at 0.008 with no speed element. This was based on 70% aspect ratio radial tires with duals on the rear drive axle.

4.9 Aero

The drag coefficient was set at 0.85 to relate to a basic cuboid form. Many transit buses are forced into this bluff outline by the combined effects of interior packaging, door requirements plus the practicalities of frame and glazing systems.

4.10 Control strategies

The basic hybrid operating strategy used the powertrain in Series Follower mode. The runs were run for Zero Delta SOC with a narrow band of 0.5% tolerance. The motor rating and battery sizing had taken careful account of the required regen capacity. The energy checks ensured that the maximum energy was recovered and losses to friction braking were minimal.

The other possible operational aspect was the ZEV option. In that this complicates the operational modeling, it was considered more useful to study the solely powertrain and vehicle issues. ZEV issues are more strongly link to the battery life-v-cost balance which is really another study. All designs developed here are capable of ZEV operation, but it is felt that ZEV range should be limited.

Although ZEV reduces the very local and immediate emissions, in fact the route emissions, and fuel use, are increased due to the battery round-trip losses. Further, if a long ZEV range is specified, the battery mass then starts to influence the total efficiency in all modes.

Newbus has studied the effects of ZEV operation and optimized control strategies, but the results remain proprietary.

5. Design Sensitivities

These runs were carried out using the NBUS_01 model of the standard baseline powertrain and vehicle. A range of parameters was studied. These parameters were varied between relatively wide limits to assess their effect on fuel consumption. Only one variable was changed at a time. All runs used maximum passenger load and the MLTB drive cycle.

Table 2: Parameters and their limits

Parameter	Lower limit	Upper limit
Engine eff, max	0.35	0.50
Generator eff, max	0.80	1.00
Motor eff, max	0.80	1.00
Battery, kWh	10	100
Final drive, ratio	3	9
Mass (glider) kg	7,000	12,000
Acc power, kW	6	30
Tire (1^{st} rrc)	0.005	0.010
Aero, Cd	0.3	1.1

6. Baseline model and related fuel economy results

The NBUS_01 standard vehicle was simulated, fully laden, over the MLTB drive cycle as described. This formed the starting point for the design parameter sensitivity study.

The base NBUS_01 fuel mileage was established at 3.82mpg.

The output from these simulations plots the sensitivity of the major parameters under study. Each of the main design functions as described in Section 4 were studied in isolation. The values were varied from the baseline specification and the drive cycles re-run. The results showed the impact on fuel consumption of these specific changes. The findings allow the strategic adoption of the usual desired characteristics for low energy vehicles. These include the expected low mass primary and secondary structures, powertrain sweet-spot operation. etc. It also sheds light on more complex issues such as the degree of hybridization and the importance of the auxiliaries & operating factors.

The design sensitivity sweeps included recording the SOC correction and any errors in vehicle speed when compared to the required vehicle speed trace. A number of the extreme cases below failed to follow the speed trace. The largest errors were in the 12 to 15kmh (7.5 to 9.0mph) band.

6.1 Diesel

The scanned efficiency values covered the range from 35 to 50%. These were factored to give the usual mapped efficiency against load values. This approach showed improvements in fuel mileage up to 39% between the limits. The 50% efficiency value was to indicate potential operation at levels achieved by fuel cells, including their auxiliaries. The results are shown in Figure 1.

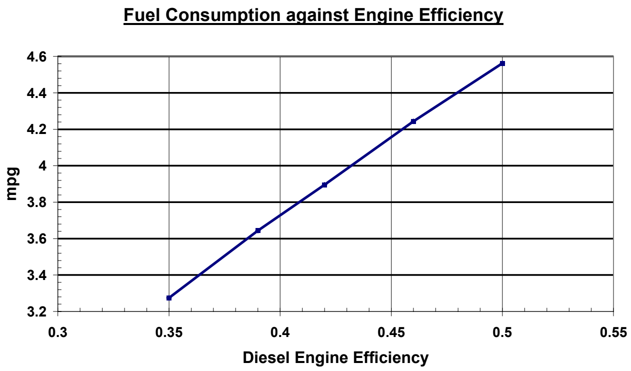


Fig 1: Mpg against Diesel Engine Efficiency

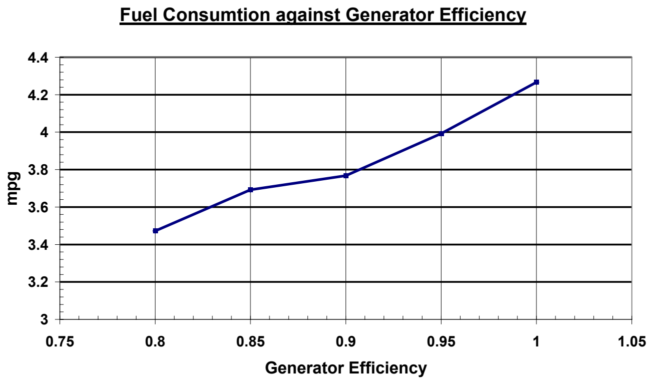


Fig 2: Mpg against Generator Efficiency

6.2 Generator

The generator was scanned from 80 to 100% efficiency limits. Since some modern units get into the high 90's it seemed relevant to see the effects of a 'perfect' machine. The best fuel results were 23% better than the low limit. The results are shown in Figure 2.

6.3 Motor

The motor was also scanned from 80 to 100%, but these maximum values related to the baseline efficiency map characteristics. The effect of this 25% gain in motor efficiency was a remarkable 47% gain in fuel mileage. This compounded effect comes from the benefits being gained on both drive and regen, with the consequent large reductions in the diesel inefficiencies. The results are shown in Figure 3.

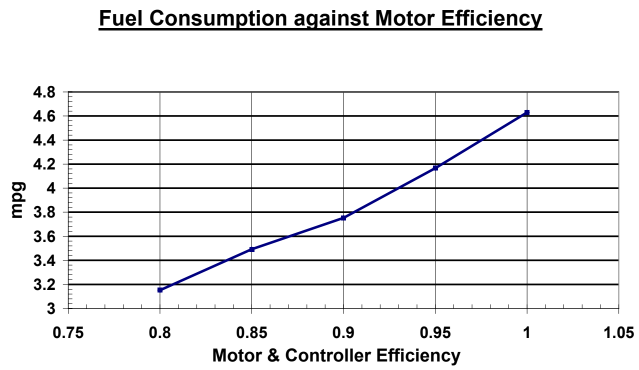


Fig 3: Mpg against Motor Efficiency

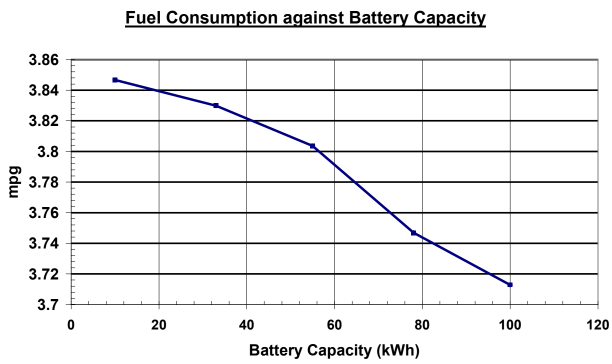


Fig 4: Mpg against Battery Capacity

6.4 Battery pack

The battery system, comprising lead acid modules, was varied in nominal capacity from 10kWh to 100kWh. This analysis obviously did not take account of the battery accumulated damage from the changes in thru-put per module. The lightest pack showed a 4% gain in mileage, but was unable to follow the cycle trace due to its reduced power ratings. The results are shown in Figure 4.

6.5 Transmission

The final drive limits were from 3.0 to 9.0:1, both extremes had operational problems. The fast 3.0 ratio could not follow the route trace due to its reduction in tractive effort. Although the lower geared, slow version delivered the best consumption figure, its geared maximum speed was right down to 49kmh (30.5mph). However this slow specification showed 39% better mileage and illustrates the potential of gearing correctly to suit the operation. The results are shown in Figure 5.

Fig 5: Mpg against Final Drive Ratio

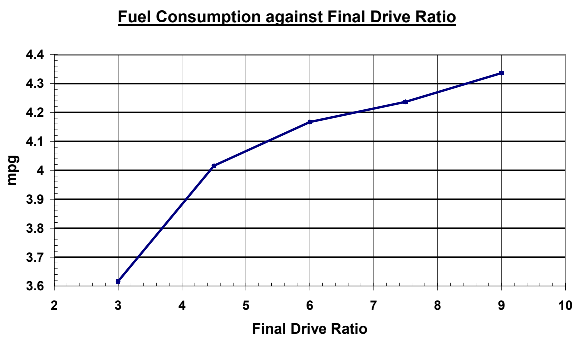
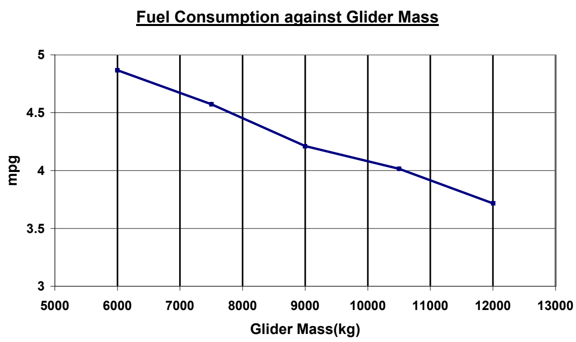


Fig 6: Mpg against Glider Mass



6.6 Mass

The glider mass scan from 6,000 to 12,000kg gave the expected large impact on the mpg. The lightest version had a 31% gain in fuel mileage compared to the heaviest case. The results are shown in Figure 6.

6.7 Auxiliary systems

The auxiliary losses were scanned over a range to cover the possible limits. Although the baseline vehicle did not include A/C, these accessory loads covered values up to 30kW that would relate to full A/C operation. Effectively the mileage doubled with the low load condition showing how critical these hotel loads are once the tractive energies are reduced. Also the power sink was so high on the max A/C versions that insufficient power was left for tractive efforts during acceleration. The A/C effects are studied in more detail below in Section 10. The results are shown in Figure 7.

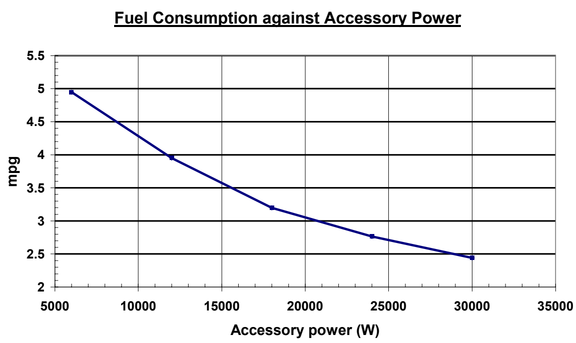


Fig 7: Mpg against Accessory Power

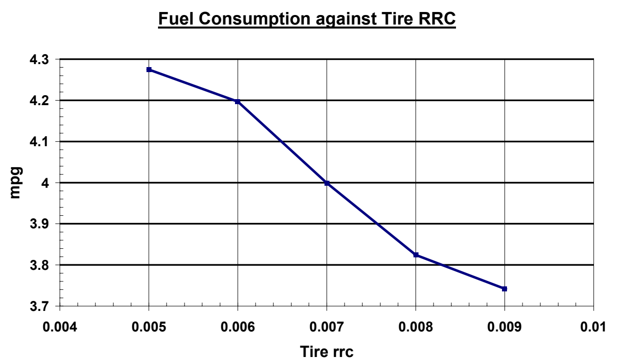


Fig 8: Mpg against Tire Rolling Drag

6.8 Tire

The tire rolling drag was scanned from 0.005 to 0.01. These were fairly conservative practical limits. The more efficient tire had 15% better mileage than the worst case tire. The results are shown in Figure 8.

6.9 Aero

The drag coefficient was scanned from 0.3 to 1.1. The low drag case showed only a 5% benefit due to the low operational speeds. The results are shown in Figure 13.

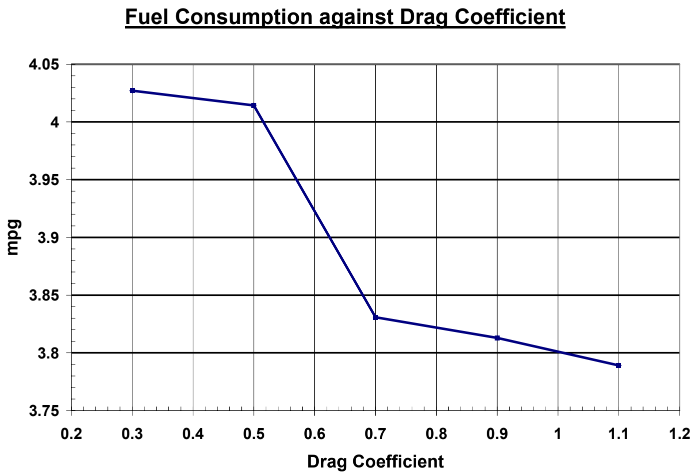


Fig 9: Mpg against Drag Coefficient

6.10 Summary of results

From the above general analyses, it can be seen that the various systems have a varying impact on transit bus energy use. Some aspects have a very highly geared effect on vehicle fuel consumption. Others have a relatively minor impact and are not going to represent good areas for detailed optimization. The sections below focus attention of the main efficiency drivers and propose specific values in some areas.

For the conversion of fuel mileage results into other units:

from mpg(US) to mpg(Imp), **multiply** the value **by 1.2**

from mpg(US) to l/100km, **divide** the value **into 235**.

7. Advanced Hybrid powertrain

The findings from the design sensitivity analysis were used to formulate two packages of modifications. The first was termed the Advanced Hybrid powertrain. This made no changes to the actual vehicle, but concentrated on the units described below. It is considered a practical proposition to incorporate this new drivetrain into an existing design of production bus. This model was run as NBUS_02.

It again maintained the acceleration and grade performance to White Book standards, but the maximum speed was reduced from 67 to 46mph by adjusting the final drive ratio. This was to match the actual operational requirements and to allow the motor to operate at a better zone of efficiency.

7.1 Diesel engine

The target characteristic is a specific fuel plot with a 'table top mountain' of high fuel efficiency. This zone was around 190g/kWh. This gave a peak thermal efficiency of 44%.

7.2 Generator

The generator specification was changed to a large diameter unit using permanent magnets (PM). This allowed a higher torque rating and so reduced engine speed for a given power. The operational efficiency band was in the 94 to 97% band compared from 89 to 92% of baseline unit.

7.3 Motor

The motor was also changed to a PM design. This allowed a design more more efficient and more compact. The operational efficiency band was in the 93 to 96% band.

7.4 Energy storage

The actual battery optimization is more complex than allowed in this study. The problem is the complexity of the effects of battery life, mass, power ratings etc. The advanced battery solution adopted for the Advanced Powertrain is a NiMH unit sized for regen power. This has a number of advantages over the base line lead acid system. Its higher power rating allows a lighter and more compact unit. Battery life, for a given thru-put, shows the promise of much increased life and reliability.

7.5 Transmission

The main issue here is the change in ratio to give a top speed in the region of 70kmh (44mph). The efficiency target remained the same at 98% per gear stage.

7.6 Overall

This package formed the basis of the second main simulation model, that of NBUS_02. The various units were developed to match the same duty cycle as the baseline bus. The vehicle and vehicle system configuration were not changed.

The fuel consumption result for this NBUS 02 model was 5.94mpg.

This was some 55% better than the NBUS_01 baseline version under the same duty. The drive cycle was again MLTB and the load condition fully laden.

8. Advanced Vehicle Configuration

The second package of design changes were termed the Advanced Vehicle specification. These were significant in scope and would not be readily incorporated into an existing bus. They relate to the bus construction, the various auxiliary systems and the tires. When combined with the Advanced Hybrid powertrain, it formed a new model, NBUS-03. The performance standards of this version were matched very closely to the Advanced Hybrid powertrain in the Standard Vehicle, NBUS_02.

8.1 Vehicle unladen mass

The NBUS_03 model has a glider mass down from 11,000kg to 7,000kg. This large change is related to changes to both construction and layout. The integral shell is fabricated in riveted aluminum. The arrangement of the major masses and loads has been optimized to reduce the structural weight. The unladen mass is 9,180kg.

From previous design projects related to products in production, the achievable values of %PF can be closely defined. There are market issues here however with the US market using higher power and heavier solutions than elsewhere. Whilst past projects have reached 50%PF, these were without A/C. The same model in service in Asia with a tropically rated A/C achieved a PF value of 45%. Since these were of regular construction, using conventional heavy duty parts, the target set here was 40%PF with A/C. These values within the NBUS_03 model give a 40%PF value.

Questions have been raised on the achievability and durability of an integral aluminum bus. A strong supporting case can be seen in the famous red double deck London buses. These are riveted aluminum integrals, carry about 80 passengers and have lasted 40 years to date. They weigh some 7,800kg unladen, that is glider plus powertrain masses. They have a 40%PF value.

8.2 Auxiliary systems

These systems have been re-configured to suit both the new vehicle and new powertrain. Electrical power is used for both the power steering and compressed air system. They use high voltage, variable speed units for maximum efficiency. The power steering pump is down-sized as it runs at higher rpm when required and now longer needs to meet the ‘dry park at idle’ criteria. The compressed air system uses a speed controlled rotary vane unit. Both systems have been rated to suit the lighter axle loads which mean lower braking, steering and suspension power absorption.

8.3 Rolling

From the baseline value of 0.008, the design target is 0.006. The tire combination uses a 70% aspect front tire with a 45% aspect ratio ‘super single’ rear tire. This combination meets the target vale for 1^{st}_rrc.

8.4 Aero

The target CD value is 0.45. Although this has a small direct effect on route results, the compounded effect thru diesel and drive units means that it is worth pursuing. The reduced aero braking directly feeds more energy into the regen system at higher speeds.

8.5 Overall

For this NBUS_03 model the Advanced Vehicle was combined with the Advanced Hybrid powertrain as used in NBUS_02. However the powertrain was re-rated to suit the lower inertial and system loads in the new configuration. This achieved some very marked savings when the compounding effect of the virtuous spiral was incorporated. Notably, the cooling fan power dropped significantly with the combination of a higher efficiency engine down-sized for the lower vehicle demands. The heat rejection to coolant, not the shaft output power, sets the fan duty. This coolant rejection (radiator plus CAC) dropped greatly so giving much lower mean fan powers.

The NBUS_03 vehicle recorded a fuel consumption of 8.16mpg.

This was 113% better than NBUS_01 baseline over the same MLTB cycle. It was also 37% better than NBUS_02, which had the same approach to the powertrain technology, showing the gains from the improvements in vehicle construction.

9. Alternate Drive Cycles

The drive cycle is a fundamental factor in rating the various vehicle systems. The issues include the usual factor relating to city operation. This type of operation combines very busy traffic conditions and drivers of varying interest in providing a comfortable ride and preserving fuel. As mentioned previously, it was considered vital that any modeling uses actual logged drive cycles to take account of these harsh conditions.

The London Bus cycle is useful as a complex operating profile in dense city traffic. This is by definition a aggressive drive cycle with low mean traffic speeds and much congestion. Part of this study was to optimize both the vehicle and its operation. The project also covered what were considered to be idealized service cycles to maximize efficiency. These had modest maximum speeds combined with straight 'ramps' for the acceleration and braking phases.

During the period of the project the organisation covering global public transportation, Union Internationale des Transport Publics (UITP) developed a set of Standardised On-Road Test cycles (SORT) for simplified comparative testing of actual buses. It was decided that we would also use these for our simulations. They utilized simple ramps and constant speed sections similar to our postulated ideal conditions. By testing against the SORT profiles, it would then be practical to carry out real world correlation with this ADVISOR work.

Table 3: Basic characteristics of alternative MLTB and SORT duty cycles

Parameter	**MLTB**	**SORT1**	**SORT2**	**SORT3**
Time (secs)	**2281**	**1530**	**1830**	**2040**
Distance (km)	**8.97**	**5.20**	**9.20**	**14.50**
Max Speed (kmh)	**49**	**40**	**50**	**60**
Av Speed (kmh)	**14.2**	**12.6**	**18.6**	**26.3**
Max accel (m/s2)	**1.50**	**1.03**	**1.03**	**0.77**
Max decel (m/s2)	**2.2**	**0.8**	**0.8**	**0.8**
Idle time (s)	**705**	**600**	**600**	**400**
Stops	**56**	**30**	**30**	**30**

Note these SORT values are for 10 cycles of the basic profiles. This increase was used to average the battery SOC correction and to provide a longer cycle to match other drive cycles. The other drive cycles cover a range of bus duties from the ADVISOR library. These include the CBD14 and Arterial profiles. The NB-IDEAL was thought to be an idealized cycle to deliver the same deliverable characteristics as the MLTB. It covered the same distance in the same time. It also reproduced the stop number and dwell time. The changes came in reducing the max speed to one steady value and using straight accel and decel ramps. This approach was to show the gains of bus-way operation, unhindered by traffic congestion.

However, these profiles gave slightly worse fuel consumption than the MLTB. It is believed that the reason lies in the straight, constant tractive effort approach rather than a curved constant power acceleration. This leads to higher peak ratings with no gain in travelling efficiency. This also applies to the points concerning the maximum performance envelope in relation to actual operational duty cycles.

Regarding the maximum envelope, the Newbus approach has been consistently to reduce the high speed and high g limit conditions. These characterize the maximum points of system operation, but can represent a very small percentage of operational running time. Hence the system rating, mass and costs parameters are excessive if high limits are set. The particular strength of this argument is that high road speeds and high accelerative and decelerative levels are contrary to user demands. This applies to various safety, noise and comfort issues.

One particular US characteristic is to operate transit buses at around 10 to 25mph in dense city traffic, but demand a 65 to 70mph maximum speed potential. When queried, this maximum is required to run down the Interstate to (say) the engine shop. This is like asking a 747 to go supersonic just to get back for a Pratt & Whitney service!

A second major driver on higher power ratings is to allow the bus to accelerate sharply into small traffic gaps. This 'step off' behavior is great for the driver, but less good for standing passengers. As a future ideal, it is the gaps in the traffic that should be larger, not the g levels, and traffic operations allowing prioritized blending of public transport systems.

The proposal is to use low maximum speed and to configure the powertrain for constant acceleration ramps. The target on regen is to match the tram ideal characteristic with no foundation braking in normal service. This is close to the SORT drive cycle.

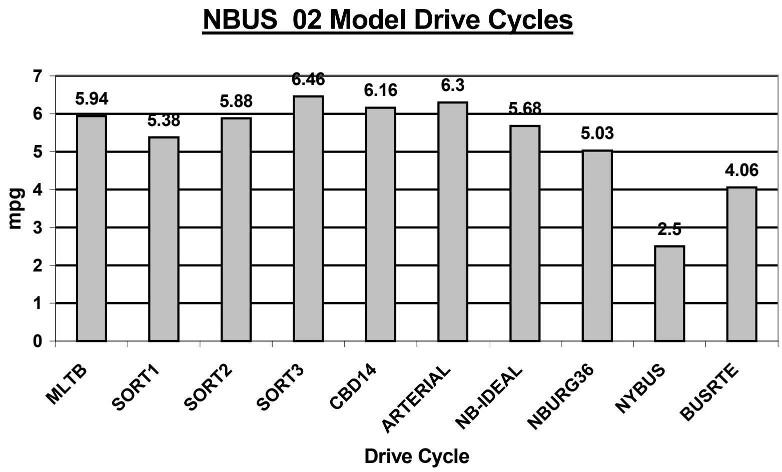


Fig 10: NBUS_02 model drive cycle results

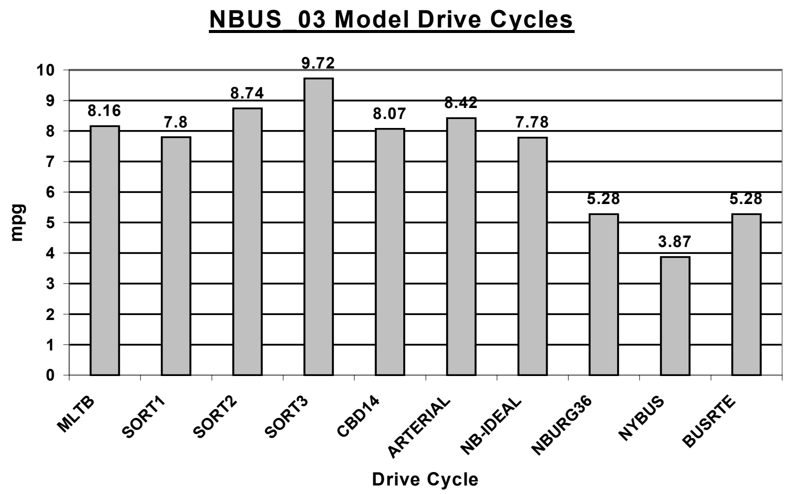


Fig 11: NBUS_03 model drive cycle results

The results are shown in Figures 10 and 11. Overall, the effect of using the Advanced Hybrid powertrain approach in an Advanced Vehicle compared to a Standard Vehicle, improved the fuel mileages by up to 55%, with an average 37% improvement over this wide range of bus duty cycles.

10. Air-conditioning effects

As mentioned, the fundamental simulation runs did not include any significant HVAC accessory powers. The models of NBUS_01, _02 and _03 only included minimal body electrical loads to cover the ventilation system and fan powers. This was to avoid the potentially very high hotel loads dominating the results from the vehicle and powertrain studies. Since the A/C loads are high, with reduced vehicle powers, they become even more critical. A separate Newbus study was carried out in parallel with this hybrid simulation covering the body HVAC requirements. In studying the fundamental A/C loads, the various heat inputs covered:

- environmental by conduction,
- solar gain
- electrical heat to air
- metabolic
- fresh air
- recirculated air.

These factors were calculated across a range of climates divided into bands set by wet bulb temperature. This wet bulb temperature relates approximately to the enthalpy of the air in terms of:

Enthalpy (kJ/kg) = 3.2 x temp wb (deg C)

This enthalpy figure quickly shows the problems in trying to chill large amounts of fresh air in hot, high humidity climates. The design case of New York, known by some as 90/90 (in terms of degree F and % RH, relative humidity) has been used to size the A/C system in the model. This requires fresh air to go from 32 deg C, 90% RH to maybe 20 deg C, 50% RH. This represents a change in enthalpy from 110kJ/kg to 40kJ/kg. This means to limit the total A/C power the amount of fresh air must be also be limited.

The single dominant input then becomes the metabolic heat input from the passengers. For the maximum 90 passenger load, this is set at 13.5kW. The other heat gains also come to 13.5kW so the system design capacity has been modeled at 27kW. This is obviously strongly linked to passenger numbers, a factor that has been studied below.

A range of A/C system efficiencies have been modeled with varying Coefficients of Performance (CoP). This CoP value factors the output cooling capacity to input power. The values assessed range from 1.5, thru the normal 2.0 to a maximum of 2.5. Additional to the cooling power, an electrical load has been added to cover the various fan powers. These calculations led to the bus models of NBUS_04 and NBUS_05 and were studied as A, B & C versions in each case. These related to CoPs of 2.5, 2.0 and 1.5. The high A/C powers greatly affected the fuel mileage as expected.

For reference purposes, the baseline Standard Vehicle, NBUS_01 with the NY A/C specification, using a CoP value of 1.5, gave a fuel mileage of 2.36mpg .

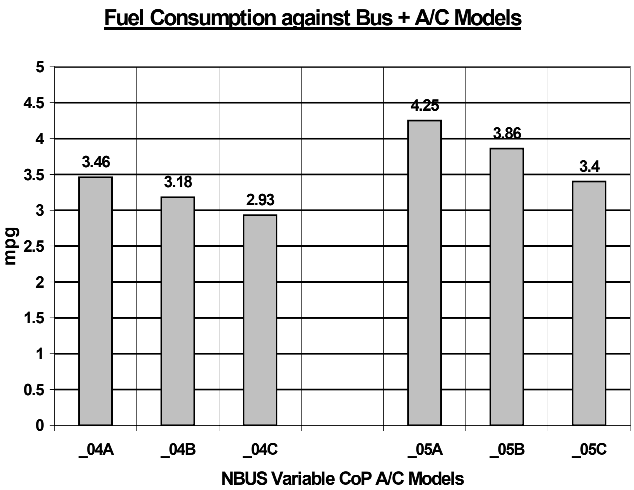
This would suggest a normal diesel mechanical bus would have a fuel consumption in the 1.9 to 2.1mpg running fully laden and full A/C power take-off. This is in line with actual service data. The NBUS_04 and NBUS_05 results are shown in Figure 12.

11. Passenger loading effects

The effect of passenger loadings was studied on both the non A/C and A/C models. These models concerned were NBUS_02, NBUS_03, NBUS_4C (A/C CoP 1.5) and NBUS_05A (A/C CoP 2.5). The passenger load was scanned from 0 to 90 passengers and all the bus models run over the MLTB drive cycle.

It was shown that the combined effect of reduced total mass, and correspondingly reduced A/C load, was very marked. The A/C models were adjusted for each passenger load condition. Since up to half of the laden A/C load could be related to the metabolic heat input, this factor needed to be included in each case.

Generally all the fuel mileages with zero passengers increased to about 140% of their max laden values due to the mass reduction and A/C saving. Also the change from the Standard Vehicle to the Advanced Vehicle, both using the Advanced Powertrain approach, improved to 145% of the Standard fuel consumption value. The results are shown in Figure 13.



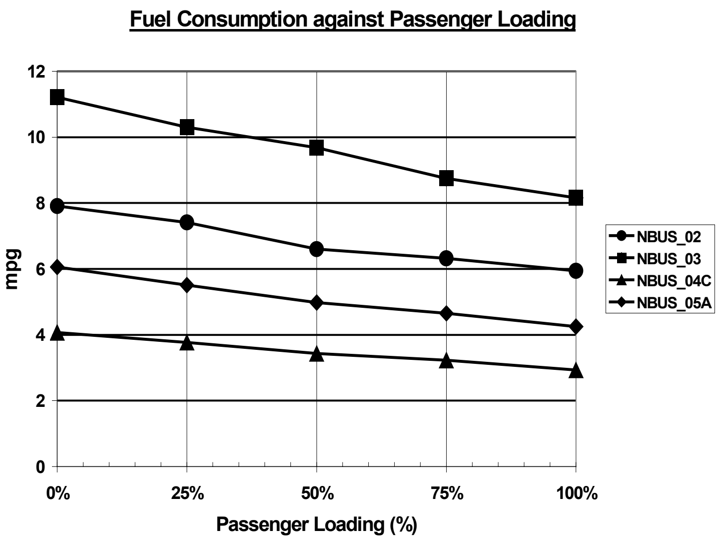


Fig 12: Mpg for NBUS_04 and NBUS_05

Fig 13: Mpg variation with passenger loading

12. Commercial considerations

This final section investigates the general effect of the commercial aspects on the vehicle design and service life operation. This can only be in qualitative, not specific, terms as a full cost study is beyond the scope of the paper. To complete an exhaustive study of these aspects would stray into the more unpredictable areas of market economics and national political agendas.

12.1 Fundamental approach

The main concept here is to expound the Newbus thesis of a lower performance envelope for transit applications. This aims to provide a relatively low speed, low g envelope to acceptably match the actual service requirement. Low speed operation improves fuel use and emissions whilst reducing noise and collision risk levels.

This contrasts with the current approach in both the car and truck markets. These sectors are characterized by ever increasing horsepower ratings. The car market quest for high power is essentially emotionally driven and not related to any mobility issues. The truck is more focussed on transport issues as operators require their minimum speed to also be their mean speed. This means higher installed powers to maintain speeds on grades etc.

The lower performance transit bus approach is much more in tune with the other requirements of modern city operation. The theme leads to lower maximum power ratings and so reduces both powertrain and system masses. These in turn are followed by lower purchase and operating costs.

12.2 Power units and energy storage

It is particularly important to minimize the cost of advanced powertrains and energy storage systems if such vehicles are to be widely adopted. It is clearly beneficial to minimize the ratings of such systems wherever possible. This is a particular challenge for Fuel Cell systems. It is also important to consider lifetime costs rather than just first costs. This needs to be on a realistic basis for all options.

12.3 Future energy costs

The motivation to use higher efficiency vehicles clearly increases as energy costs rise. The current economic climate suggests that there is upward pressure on the specific energy costs for diesel, CNG and LNG. It is likely that these pressures will also apply to the alternatives of hydrogen and generating grid electricity. Other important factors include fuel availability and the influence of government policy, usually implemented through taxation changes. A change in the type of fuel used also generally implies large infrastructure deployment costs.

12.4 Design optimization cost pressures

Significantly higher energy costs become an enabler for more advanced forms of lightweight construction and efficient powertrain architectures, which generally tradeoff higher first cost against lower operating costs.

13. Conclusions

The simulation work has studied the fundamental energy balances within a typical hybrid transit bus. The work covered both the absolute fuel mileage values and the sub-system share within the total system of a baseline design of heavy-duty transit bus. The work continued to study the overall efficiency in terms of its sensitivity to these sub-systems. These were modified in arbitrary step changes in energy loss to assess their effects on fuel consumption.

The extension of the sensitivity analyses was to evaluate potential, near-future design changes in transit bus design. These changes were studied into two packages relating to an achievable future product. This section showed potential increases on both actual service and simplified operating cycles from 155 to 215%.

From this work it is suggested that realistic gains in transit bus fuel mileage could be delivered in the band of 1.5 to 2.2 times the fuel performance of the basic hybrid bus. These require design development for both powertrain and vehicle. It is suggested that gains in the band 2.5 to 3.0 are not practical mainly due to the probable accessory loads being dominated by the A/C requirements. The overall effects however supported the previous research findings and showed similar gains in efficiency.

The extensions to this work covered various drive cycle, passenger loading and A/C system combinations. It was seen that as the tractive loads are controlled, the impact of full 'hot & humid' A/C operation is very marked. On both the Advanced Hybrid and Advanced Vehicle models, the full mileage was halved with full A/C operation. Newbus is currently studying some alternate avenues to reduce this burden.

The central conclusion of the work to date, and still in progress, is that to facilitate the commercial delivery of advanced electric drives, the total energy and maximum power ratings of the systems must be reduced. To achieve this goal, the sensitivity studies show that certain inherent vehicle characteristics require re-configuring for this new technology, for this new era.

Essentially, the optimized vehicle solution requires a 'new bus' design to deliver on the promise of greatly improved city mobility, coupled with similar gains in air quality. The resulting product is significantly closer to the ideal that most cities now require.

The overall proposal is that for attractive and sustainable city transport, we need to use less energy and hence design our city transport vehicles accordingly. It is suggested that the developed world must learn this lesson, or will be taught it.

14. Acknowledgement

The authors would like to thank Michael O'Keefe and his colleagues on the ADVISOR team at NREL for their speedy response to questions about the internals and facilities of ADVISOR.

15. References

[1] Robert J Shapiro, Kevin A Hassett and Frank S *Arnold Conserving Energy and Preserving the Environment: The Role of Public Transportation, July 2002*. This report was commissioned by the American Public Transportation Association.

[2] Mike Kellaway and Alan Ponsford, Newbus Technology Limited. *Hybrid buses – the benefits of matching to real routes* NREL ADVISOR Uses Conference, August 2000.

[3] Government-Industry Research Partnership. *Technology Roadmap for the 21st Century Truck Program, 2000* US DOE Information Bridge

16. Authors

Alan Ponsford, Director, Newbus Technology Limited. Alan studied Mechanical Engineering at Imperial College, London before completing his heavy vehicle training at Leyland Motors. He established Capoco Design, a bus, coach and truck design company in 1977. This company continues with its conventional bus design projects across five continents. He is joint founder of Newbus Technology, a company established in 2000 to address the sector of electric drive buses, both hybrid and fuel cell.

Mike Kellaway, Newbus Technology Limited. Mike studied Engineering at Churchill College, Cambridge before completing his heavy vehicle training at Leyland Motors. His work in recent years has been in vehicle electric drives and associated control systems. He is joint founder of Newbus Technology, a company established in 2000 to address the sector of electric drive buses, both hybrid and fuel cell.

Address:	Newbus Technology	Stone Cross House,	Chicksgrove,	Salisbury SP3 6NA UK
Contact:	Tel +44 1722 716 722	Fax +44 1722 716226	Email	technology@newbus.com

Newbus Technology Document Code: Newbus030815.1.USHybridTransitBus.doc