# Evaluation of a Hybrid Hydraulic Launch Assist System for use in Small Road Vehicles

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Abstract – Hybrid hydraulic launch assist (HLA) vehicles capture energy during vehicle deceleration by compressing fluid in a hydraulic accumulator system. The hydraulic accumulator system can then be used to provide torque at a subsequent vehicle launch. HLA systems are usually aimed at heavy vehicles which have a large amount of kinetic energy available for capture. This article, however, discusses the application of HLA systems on small road vehicles in urban driving conditions by modeling and simulation. The results show that fuel economy savings are not as high as those previously predicted, although many opportunities for system improvement are highlighted by the research approach. It is concluded that with further, more specific, research and development, the HLA system could have a valuable roll to play in the future of hybrid road vehicles.

#### I. INTRODUCTION

Hydraulic launch assist (HLA) vehicles have been considered as a possible option for renewable energy and hybrid vehicle systems for a number of years. It was not, however, until digital control technology in vehicles became more advanced that R&D teams began to consider the system as a viable option.

Given early excitement in the concept, there still remains no commercial hydraulic launch assist vehicle on general sale. The US army are known to have invested in this technology [1], but it is unclear as to how committed they are to HLA systems after their initial R&D efforts. Similarly, many of the early studies into HLA technology have focused on heavy-duty trucks and buses, as the heavy mass of these vehicles creates a large amount of energy which can potentially be reused [2][3]. However, it is believed that many advantages can be made by using the HLA system in small vehicles in urban driving scenarios, such as city delivery vans and taxis. The anticipated advantages are predominantly owing to the fact that such vehicles experience many start-stop events, idling in traffic and prolonged operation at the internal combustion engine's least efficient region of low revs and vehicle speeds [4].

A hydraulic launch assist system can be regarded as a standard parallel hybrid vehicle setup, except whereas many hybrid vehicles use battery storage and electrical energy to assist vehicle propulsion, the HLA system utilises a hydraulic accumulator system to capture energy during braking and to regenerate this to assist with acceleration at launch.

This paper discusses the design of a HLA vehicle system and implementation on a small road vehicle by modeling and simulation. Model based design techniques are used to reduce the development time for a final prototype vehicle system. Vehicle simulation is used to evaluate key system design parameters, such as the energy storage capacity, as well as to discuss the results of the system performance

against conventional vehicles in drive cycle tests. The results of this simulation therefore add to the existing knowledge and understanding of opportunities and design and control issues for HLA hybrid vehicles, particularly with respect to their applicability to small urban vehicles.

#### II. HYDRAULIC SYSTEM MODELING

The standard HLA system comprises a reservoir of hydraulic fluid at low pressure. A second (piston segregated) chamber contains pre-pressured nitrogen and acts as a hydraulic accumulator for energy storage. The nitrogen chamber in the hydraulic accumulator can be further pressurised by pumping in hydraulic fluid from the reservoir. The volume of fluid pumped to and held in the accumulator therefore has a direct relationship to the nitrogen pressure and the potential propulsion energy stored at any moment in time.

A hydraulic pump is used to transfer fluid between the low pressure reservoir and the accumulator. A particular pump designed for the purpose of HLA is the axial piston pump developed and discussed by Frazer et al. [5]. An axial piston pump is the ideal choice for such systems as it allows the input/output torque and fluid flow rate to be dictated and controlled by the angular position of an internal swash plate. The hydraulic pump is attached to the driveline system and can be engaged during a vehicle braking event. This allows wheel braking torque to be made up predominantly of the inertia in the hydraulic system, and thus removing the torque demand on the conventional braking system. In retarding the vehicle, the HLA system pumps fluid to the accumulator unit, pressurising the contained nitrogen gas.

If the hydraulic system is energised and the vehicle driver chooses to accelerate, the stored hydraulic energy can be used to launch the vehicle and reduce the required torque from the conventional internal combustion engine (ICE). The hydraulic pump therefore acts as a hydraulic motor during acceleration events. In order to assist acceleration, the input and output ports to the hydraulic pump/motor must be reversed. This is owing to the fact that vehicle motion is always in the same direction (forwards) regardless of whether the vehicle is braking or accelerating. Without reversing the port orientation the vehicle would capture energy while braking moving forwards, but would return energy by attempting to move the wheels in the reverse direction.

The hydraulic system is modelled by simulation of a number of key systems (see Figure 1). The hydraulic system is coupled to the main drive system by a gear set allowing torque to be delivered to the wheels by multiple sources. Given the efficiency and ratios of this gear set, it is therefore possible to calculate the effective wheel torque.

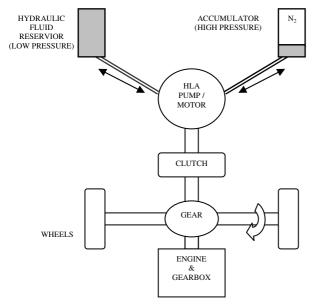


Figure 1. Shows the torque generation systems for the hybrid HLA vehicle. The Engine (via the torque converter and gearbox) can provide torque, as can the HLA system. The HLA system pumps hydraulic fluid from the reservoir to the accumulator during braking, pressurizing the contained nitrogen. The pressurized accumulator is then used to drive the hydraulic motor and provide torque at launch.

A HLA system for a small road vehicle can weigh approximately 200kg and comprises the following system components, as shown in Figure 1 and described below.

#### A. Axial piston pump

An axial piston pump (based on Frazer et al.'s design) which is capable of transferring hydraulic fluid from the reservoir to the accumulator and vice-versa. The pump can be driven mechanically to produce fluid flow (i.e. during vehicle braking) or it can use fluid flow under pressure to deliver mechanical torque (i.e. during vehicle acceleration). The amount of fluid transferred and the amount of torque output are controlled by the angle of the piston pump swash plate. If the swash plate is set to zero degrees then no fluid can flow. The performance data for the axial piston pump has been gathered by empirical testing, as shown in Figure 2.

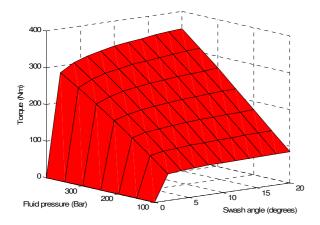


Figure 2. Shows the torque generated by the hydraulic pump/motor against swash displacement angle and hydraulic fluid pressure.

# B. Hydraulic fluid reservoir and accumulator chambers

At the steady (uncharged) state, all the hydraulic fluid is contained in the reservoir chamber. In this case (and with reference to default simulation parameters), 3.56kg of nitrogen is pressurised in the accumulator chamber which measures 18 litres in volume. The nitrogen is therefore initially pressurised to 172 bar at an ambient 20°C. By comparison, the reservoir chamber is closed and at atmospheric pressure. As fluid is pumped to the accumulator chamber, the nitrogen gas is pressurised to become fully charged. The overall compression ratio used is 2:1, and at this stage the nitrogen pressure becomes 344 bar, which results in an energy storage capacity of 215kJ. The accumulator chamber is filled with heat absorbent material to ensure that the compression of the nitrogen gas is isothermal. The energy stored in the accumulator at any moment in time can therefore be calculated by the first law of thermodynamics, i.e:

$$W = \int_{1}^{2} P dV = P_{1} V_{1} \ln \frac{P_{1}}{P_{2}}, \qquad (1)$$

where W is the reversible work done in compressing the nitrogen, P is pressure and V is volume. Subscripts I and I refer to values before and after compression. Standard SI units are assumed.

The 215kJ capacity is chosen to accommodate the amount of kinetic energy available for capture from a vehicle of 1500kg retarding from 60kph to 0kph. It can be seen here that many vital design parameters are available for manipulation. However, as each parameter affects the choice of every other parameter, it is exceptionally difficult to design the perfect HLA system without the aid of simulation. The values discussed above and herein have been chosen as suitable simulation parameters by detailed calculation and refinement with respect to the simulation results.

The control and switching of the hydraulic pump and valves between energy capture and energy reuse modes can be very challenging in reality, particularly when considering the high fluid pressure levels involved. These complications are not explicitly modeled in the present simulation.

### C. Geared coupling

A geared coupling effectively couples the hydraulic pump to the vehicle driveline. The hydraulic pump has a maximum speed rating, which is usually much greater than the wheel velocity of a road vehicle. In the case of the Frazer's axial piston pump, the maximum speed is 4800rpm. So, for example, adding a 2.1:1 step down gear ratio to the vehicle's final drive ratio of 3.9:1 means that, with 29cm radius wheels, the maximum vehicle speed that the hydraulic system can operate at is 64kph. This gear ratio also means that the (approximate) maximum 300Nm of torque delivered by the HLA system is geared up to approximately 2500Nm of available wheel torque when the HLA system is fully charged.

## D. Mechanical clutch

A mechanical clutch is required to decouple the hydraulic pump and entire HLA system from the driveline at vehicle speeds above the maximum operating limit.

# III. VEHICLE MODELING

The vehicle model used in simulation is based on the design and performance of an automatic Ford Mondeo.

The vehicle model calculates torque production from the internal combustion engine given a torque request command from the main hybrid vehicle controller. The specific torque command controls the throttle position and hence deduces the actual torque delivered and the fuel used in delivering the torque. The vehicle engine model used is based on the model described by Crossley and Cook [6].

Engine torque is delivered to the wheels through a torque converter and automatic transmission. The simulated operation of these devices is governed by a number of vehicle control strategies. Here for example, gear changes are anticipated and processed, and throttle reduction demands for gear shifts are processed in order to override the torque demands requested by the main hybrid controller.

The vehicle dynamics are calculated at the wheels to deduce the overall acceleration and velocity of the vehicle. In general wheel acceleration  $\hat{\theta}_w$  is calculated simply by

$$T_{w} = J_{w} \ddot{\theta}_{w}, \qquad (2)$$

where  $T_w$  is the resultant wheel torque and  $J_w$  is the vehicle's effective moment of inertia as seen at the wheels.

There are two key inertias effective on the vehicle when the hybrid system is disengaged, those of the engine and the vehicle mass as an effective inertia on the wheels, as shown in Figure 3. It is therefore necessary to calculate the effective inertia of the engine as seen at the wheels in order to calculate the vehicle motion. The effective inertia of the engine (at the wheels) is dependent on the gear ratio of the transmission and the amount of torque being passed by the torque converter. Similarly, in order to calculate engine velocity, the effective vehicle inertia as seen at the engine must be considered, particularly when the vehicle is retarding and the engine is effectively being driven by the momentum of the vehicle (i.e. engine braking).

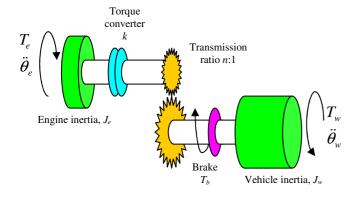


Fig. 3. Shows the inertia systems, torque and resulting motion for the vehicle model. Where J is moment of inertia, T is torque,  $\ddot{\theta}$  is the resulting acceleration, k is the torque converter coefficient, n is the gear ratio. Subscripts e, b and w relate to the engine, brake and wheels respectively.

The vehicle braking system is modelled as a simple transfer function effectively supplying the demanded braking torque, though with a filtered response to simulate the natural delay and response of a standard vehicle braking system. However, it is not simple to assume that a conventional mechanical braking system is suitable for the hybrid vehicle. During deceleration events the braking torque is desired to be provided by the HLA system, using the resistive torque of the hydraulic pump to slow the vehicle. As the accumulator becomes charged with energy, the conventional braking system needs to take over if further retardation is required. For this to be possible, a form of brake-by-wire system must be implemented so that conventional brakes can be activated as required by the hybrid system controller.

# E. Modeling Environmental Forces

Environmental forces such as road friction, gravity and drag are calculated and equated as resistive torques in calculating the vehicle acceleration and velocity. For example, the vehicle drag force  $F_d$  is calculated by

$$F_d = \frac{1}{2} \rho v^2 C_d A,$$
 (3)

where  $\rho$  is the density of air, v is the vehicle velocity,  $C_d$  is the vehicle drag coefficient and A is the projected frontal area of the vehicle.

The total environmental retarding force  $F_{ER}$  is converted to a retarding wheel torque  $T_{ER}$  by

$$T_{ER} = F_{ER}r, (4)$$

where r is the rolling radius of the vehicle wheel.

#### IV. DRIVER AND DRIVE-CYCLE MODEL

The vehicle simulation model is tested against a number of drive cycle scenarios in order to assess the performance of the HLA system. In particular the Urban Dynamometer Driving Schedule (UDDS) and the Supplemental Federal Test Procedure (SFTP) have been used for analysis (see [7] for specific drive cycle details). These drive cycles test urban driving scenarios for which the hybrid HLA vehicle is targeted. These cycles therefore describe multiple stop-start cycles with low vehicle speeds.

The vehicle driver is modeled by proportional speed control against the test cycle setpoint. This method for driver modeling was chosen because a proportional system more suitably mimics the ability of a human driver to achieve a desired speed setpoint than that of a derivative or integral control model [8].

#### V. HYBRID SYSTEM CONTROL

Control strategies for governing the power distribution of the hybrid torque sources are also developed within the simulation model. The hybrid system controller (HSC) effectively looks at the driver demand – in terms of a desired speed setpoint – and converts this into various torque demands on the vehicle. The HSC has to decide how much torque to request from each torque source. The three available torque sources being: the internal combustion engine (for acceleration torque), the braking system (for deceleration torque) and the HLA system (which provides both acceleration and deceleration torque).

There are a number of obvious control strategies which the HSC must govern. For example, during an acceleration from standstill event, the HSC should first request torque from the HLA system. If more torque is required (to accelerate faster) then additional torque should be requested from the ICE. Furthermore, as the HLA system uses up its stored energy, the amount of torque request of the engine should be gradually increased. However, to achieve this control, it is essential that the controller knows how much torque is available from the HLA system at all times. It is not possible to actually measure the amount of torque stored in the hydraulic accumulator, it is only possible to measure physical properties such as pressure, volume (by piston displacement) and temperature. The HSC therefore needs to predict the amount of available HLA torque in order to function. This prediction can only be made by mapped data of the performance and efficiency of the hydraulic pump/motor given the measured system properties.

The hybrid system controller, amongst other tasks, must also provide the following control strategies:

- At speeds above the maximum pump/motor operating speed, the HLA system must not be used. The HSC must therefore, above the maximum hydraulic pump/motor rpm, reduce all HLA torque requests to zero, and physically disengage the HLA from the vehicle driveline by operating the HLA system clutch.
- Control of the hydraulic pump/motor swash plate requires detailed control. The plate can only move from the closed position to the open position in a finite time. Therefore predictions must be made for choosing the correct time to process activation and deactivation.
- Valve port switching control is critical when switching a fully charged HLA system from 'capture' to 'reuse'. Switching hydraulic valves from one position to another with hydraulic fluid at 300bar is not a simple task and requires advanced closed loop control.
- Safety control is essential in a hybrid HLA vehicle. Control strategies need to be implemented in order to deduce what action to take in events such as a vehicle crash or system failure.

A key advantage of implementing simulation and model based design is the fact that control issues can be identified and suitable strategies can be implemented early in the development cycle. Such identified issues will be discussed in more detail in Sections VI and VII below.

#### VI. SIMULATION RESULTS

Example simulation results are shown in Figures 4-9 for a 200 second drive cycle. Figure 4 shows the vehicle drive cycle data in kph against time. The setpoint drive cycle data is shown alongside the actual speed attained by the proportional driver model. It should be noted that how close the achieved speed matches the desired speed is relatively insignificant providing the vehicle simulation encounters a number of scenarios to test and verify the performance of the HLA system.

Figure 5 shows the distribution of torque as seen at the vehicle's wheels. It can be seen that for the initial acceleration event the ICE is the sole provider of torque. During the first deceleration event the conventional brakes

are used to slow the vehicle, but as the vehicle speed drops below the 64kph threshold, the retarding torque becomes provided by the HLA system. During the proceeding acceleration event, the torque is predominantly provided by the HLA, with a small contribution from the ICE. As the HLA system discharges (see also Figure 9), the ICE takes over to provide the acceleration torque until the HLA system is recharged by another deceleration event. It can also be seen during the final deceleration event that the HLA becomes fully charged and so the conventional brakes are activated to complete the retardation to rest.

Figures 6 and 7 show vehicle simulation data including engine speed, gear position, torque converter engagement coefficient and throttle position.

Figure 8 shows the fuel consumption for two simulation runs; one with the HLA engaged, and a control simulation with the HLA system removed. Figure 8a shows the cumulative fuel use and Figure 8b shows the fuel use integrated per second. It can be seen that despite the extra 200kg weight, the HLA system does provide overall fuel savings. However, these fuel savings are not excessive and are limited to the periods of acceleration from a slow speed.

The total fuel savings observed in simulation for the entire UDDS and SFTP drive cycles are shown in Table 1.

Table 1. HLA fuel savings.

	UDDS Fuel	Fuel	SFTP Fuel	Fuel
	Use (g)	Saving	Use (g)	Saving
Standard	1291.5		807.2	
Vehicle				
HLA	1165.0	9.80 %	747.1	7.45 %
Vehicle				

The simulation exercise also allows different system parameters to be evaluated before a final design is agreed. For example it is possible to perform simulation analysis with a number of different capacity HLA systems, to verify that the desired amount of energy is being captured, and that the system is not over engineered for the amount of energy available for capture. Figure 9 shows the energy captured by the HLA system for the 200 second test drive cycle. It is difficult to estimate the actual amount of energy which can be captured during a braking event, particularly as the conventional brakes might be employed at various times and the amount of brake torque required will be erratic in response to actual driving conditions. It is therefore possible to make estimates using standard engineering principles, but simulation is an essential process to verify and improve these projections. It can be seen from Figure 9 that the 18 liter system allows much more energy capture and reuse than the 12 litre system. This can be seen by analysis of the key energy capture events at approximately 65, 85 and 120 seconds. However the 24 litre system does not offer a great amount of extra energy storage at during these periods. Given the fact that a larger capacity HLA system brings additional mass to the vehicle, it is very difficult to estimate the optimum accumulator volume. Simulation allows relevant scenarios to be evaluated, and in this study the 18 litre system appears to give a good compromise between storage capacity and system weight.

The results shown in Figure 9 also give a key indication of some of the control strategies which must be employed to maximize the performance of the HLA system. It can be seen, for example, that there is always some energy left in the HLA system after each acceleration event, and the amount of energy left unused is not the same each time. Similarly, the HLA system is not always charged to the same level during braking. The reason for this disparity is because the rate of energy charge or discharge is rarely uniform, and it is impossible to predict the driver action at any moment. It also takes a finite amount of time for the hydraulic pump swash plate to move from fully open to fully closed and vice-versa. Therefore, if the vehicle is braking and the unit is charging with energy, the torque governor must roll off the amount of torque request of the HLA system and increase the conventional brakes' contribution as the system becomes fully charged. The HLA controller must therefore make a safe prediction in order to ensure that even if a sudden large torque request is required, the system will be able to provide the required torque without the system suddenly reaching capacity. Similarly, for HLA discharge, the ICE must gracefully take over from the HLA as the regenerated energy is used up, so the HCS must activate the swash close procedure at different points dependent on the rate of energy discharge. It is hence evident that more advanced mapped strategies for HLA engagement and disengagement will allow the HLA system's performance to be maximized and increase the overall system fuel savings.

# VII. CONCLUSIONS - THE FUTURE FOR HYDRAULIC LAUNCH ASSIST

It is obvious that the theoretical fuel savings of 30-70% predicted in previous studies (for example, [9] and [10]) are very difficult to achieve in reality – especially when taking the additional mass of the hybrid system into account. This simulation shows only a 7-10% improvement in fuel efficiency on urban drive cycles, and it must be remembered that the added weight of the HLA system will actually cause fuel use increases during some driving scenarios. However, this design and simulation research has highlighted a number of ways in which the performance of hydraulic launch assist systems can be practically enhanced with further development and research.

For example, even the urban drive cycles do not evaluate performance during heavy traffic congestion scenarios, where crawling and regular stop-start events can be expected. Furthermore, as the internal combustion engine is not required for launch motion in congested situations, the HLA system makes a very strong case for integration with an engine shut-off strategy system. This could maximize the benefit of the HLA system and indeed make it a viable option for development in small road vehicles for urban use. By analyzing the extra fuel savings available with the presented simulation results, it is predicted that fuel savings could be doubled with the inclusion of engine shut-off strategies. Furthermore, the ICE is at its least efficient at low revs and vehicle speeds, and although exhaust emissions have not been investigated in the current research, it can be envisaged that these hybrid vehicle control

strategies can considerably improve exhaust cleanliness over and above the actual fuel use savings.

Simulation has also highlighted a number of complex prediction and control strategies which should be implemented to maximize the energy reuse capability of the HLA system. Implementation of these systems will also give further fuel economy improvements. For example, the HLA system is required to shut off at 64kph to avoid overrun of the hydraulic pump/motor, however a novel variable gearing could allow higher speed operation and reuse of more kinetic energy during braking.

System design parameters have also been investigated in simulation, as it is particularly difficult to predict performance characteristics from simple engineering principles alone. It has been seen that there will be an optimum accumulator size, though it is evident that further investigation should be pursued to clarify the exact constraints and opportunities with this design optimisation. Similarly, enhancements to HLA system packaging, weight reduction and the choice of operating pressures and compression ratios can only serve to maximize the energy reuse and fuel savings of such a device.

One key hurdle, however, is the safety implications of such a hybrid system. There is currently very little research into how a system might be shut down in the event of a vehicle crash. Likewise, the consequences of the accumulator, stored with 200kJ of energy explosively failing have not been sufficiently evaluated to date.

In conclusion, it appears that the HLA system is a viable option for small road vehicles, though current knowledge and research is a long way off providing a complete solution. With the advancement of physical design, control strategy development and safety systems development the HLA system should have a valuable role to play in the future of hybrid vehicles.

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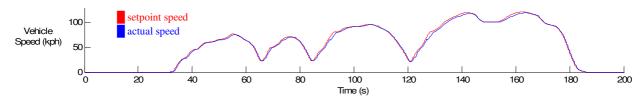


Figure 4. Vehicle speed chart showing desired speed set points and actual speed achieved by the driver model.

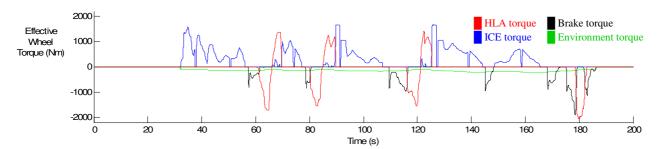


Figure 5. Effective wheel torque equated for ICE, HLA, braking system and environmental resistances.

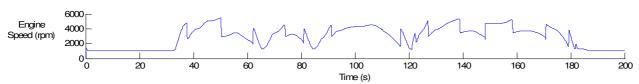


Figure 6. Simulation data for engine velocity.

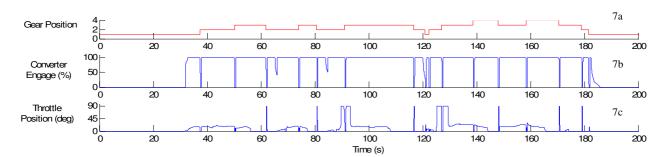


Figure 7. Simulation data for gear position, torque converter engagement and throttle position.

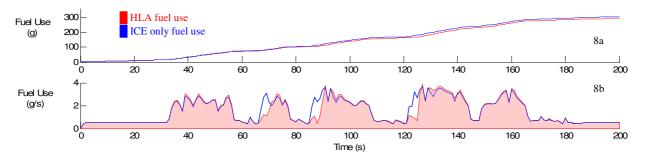
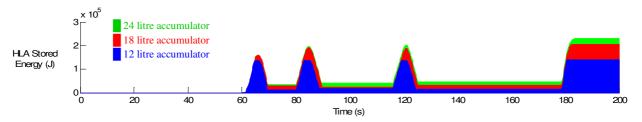


Figure 8. Fuel use charts for cumulative fuel use and fuel use per second. Fuel use is calculated for the HLA vehicle and a standard ICE only vehicle. The fuel use for the HLA system is shaded to make it simpler to identify the fuel savings made during acceleration events.



 $Figure\ 9.\ Energy\ stored\ in\ the\ HLA\ system\ for\ 12\ litre,\ 18\ litre\ and\ 24\ litre\ accumulator\ chambers.$