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New Technology Research & Development Program
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Task 1 Deliverable

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Report on the Design of Eaton Corporation's Hydraulic Launch Assist™ (HLA®) System

TCEQ Contract Number: 582-5-65591-0010

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by the State of Texas
through a grant from the Texas Commission on Environmental Quality.

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April 20, 2006

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Introduction

This report describes the results of a portion of the work funded in part by the State of Texas, through a grant from the Texas Commission on Environmental Quality. The activities and results discussed in the report are limited to the design portion of the grant requirements

Background

An Eaton Hydraulic Launch Assist™ (HLA®) System comprised of concept hardware has been previously installed in a class 8 refuse truck and tested. The concept hardware was not originally designed for use on heavy-duty trucks and therefore was not a commercially viable design. This report covers the upgrades made to the HLA System to make it more suitable for a refuse truck application.

The HLA System accomplishes its function by utilizing hydraulic components. Because of the high power density of hydraulic machines, they are well suited for application on heavy-duty vehicles. The frequent start and stop nature of refuse truck drive cycle makes it an ideal application for the HLA System.

HLA System concept and design intent

The HLA system can be used to improve the fuel economy, emissions, and/or performance of vehicles. The HLA system performs a process known as regenerative braking. The HLA system stores energy captured during braking and returns, or regenerates, that energy to assist in vehicle acceleration.

A vehicle in motion has a certain level of kinetic energy because of its mass (weight) and it's velocity. It may also have significant potential energy due to its elevation, e.g. after having climbed a high hill. Whenever a vehicle is brought to a stop, or descends a long hill, it is necessary to diminish its kinetic and potential energy in some way. The vehicle service brake performs that function. Typically, as the main braking system on a vehicle, the service brake consists of a number of friction pads that rub on a metallic drum or rotor at each wheel. When the service brake is applied, these brake pads are pushed against the drums or rotors with very high force. The resulting rubbing action, or friction, converts the vehicle's kinetic energy into heat. Hence, typical vehicle service brakes are only capable of "wasting" energy. The HLA system offers an energy efficient alternative.

The HLA system is designed to work in parallel with a vehicle's normal service brakes, not to replace them. Rather than wasting all a vehicle's kinetic and potential energy during a stop, the HLA system allows a portion of a vehicle's energy to be converted and stored as pressurized gas. During acceleration, the HLA system returns that stored energy to the vehicle by providing torque to the driveline to accelerate the vehicle. This process of temporarily storing braking energy and then returning it to the vehicle is commonly referred to as regenerative braking.

Through regenerative braking, the HLA system reduces the load on the vehicle's engine during acceleration. Engines have high fuel consumption and emissions generation during heavy acceleration. Reducing the engine's load during this mode significantly reduces fuel consumption and emissions. Consequently, the HLA system can provide a dramatic improvement in fuel economy and reduce exhaust emissions, especially when used in stop-and-go driving conditions. If used to improve vehicle performance, the HLA system adds torque to the driveline without significantly modifying engine operation. An additional benefit of the HLA System is increased brake life.

Previous design

The HLA System concept hardware consisted of a 250 cc/rev pump/motor was connected to the vehicle driveline through a transfer case with a gear ratio that increased the pump/motor torque output. The pump/motor and transfer case were mounted to the truck separately. They were connected with an intermediate shaft containing a universal joint. The transfer case contained a dog clutch that could be engaged with the vehicle at a slow creep or disengaged at any speed.

The pump/motor had two fluid ports: one for low-pressure and the other for high-pressure. From the low-pressure connection, a hose assembly branched out to a pair of 40 liter low-pressure accumulators. Filter manifold assemblies were plumbed in line in each branch from the pump/motor to the low-pressure accumulators. Likewise, from the high pressure connection on the pump/motor a hose assembly branched out to a pair of 40 liter high-pressure accumulators (no filter manifold assemblies). This system architecture was a closed system, meaning that the hydraulic fluid was never at atmospheric pressure.

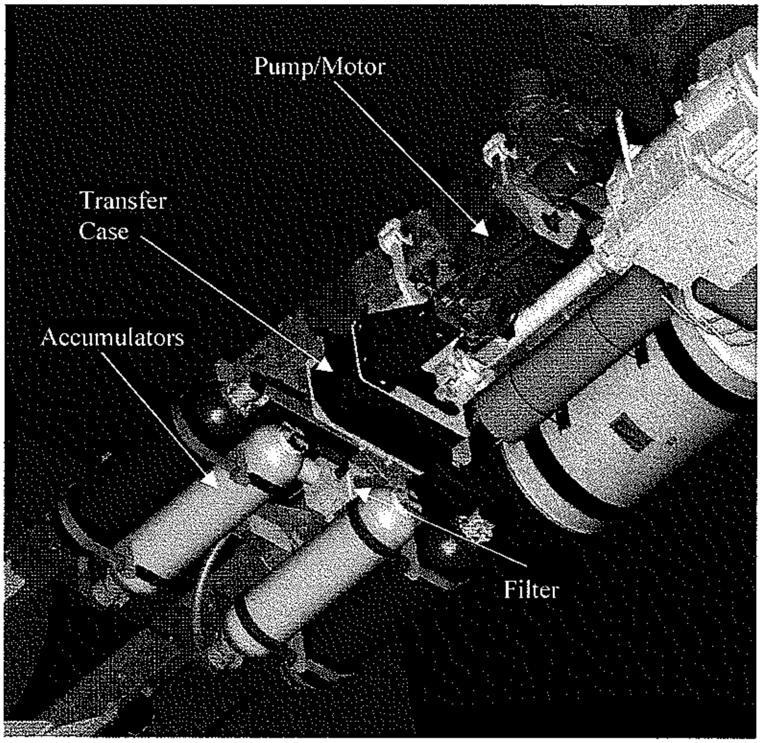


Figure 1: Concept prototype system before design improvements.

Updated Design

The design of the HLA System was updated to improve the system performance, manufacturability, serviceability, and vehicle packaging. Changes were made at the component, system, and vehicle level.

End User Data Collection

Vehicle driving behavior has a large influence on a vehicle's fuel consumption and emissions, and the ability of the HLA System to improve those metrics. In order to make the appropriate design decisions, information on real vehicle driving was needed.

Data acquisition equipment was placed on refuse trucks at a number of locations. Duty cycle data was recorded on a variety of routes and truck types during actual trash collection. This data was analyzed and the results used to help determine the optimum values for system parameters such as accumulator size, pressure ranges, and transfer case ratio.

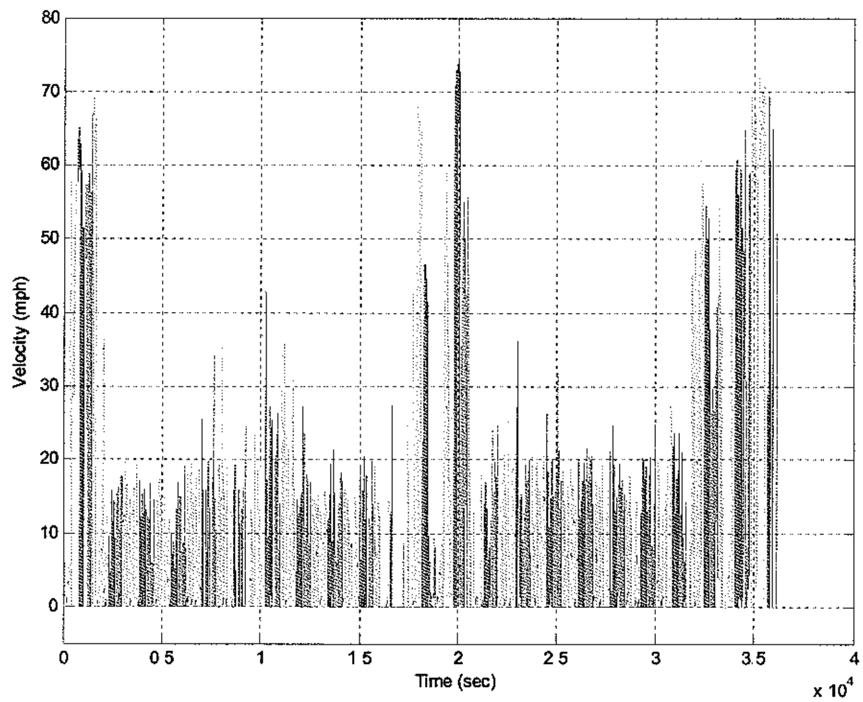


Figure 2: Example of end user drive cycle data.

System Sizing

An optimization procedure was created that uses the "real world" drive cycle data, knowledge of HLA system operation, and assumptions on the HLA system value to end-users. This procedure indicated that one 52 liter high pressure accumulator was better than two 40 liter accumulators; there were slight improvements in performance with the second accumulator, but the benefits were not justified by the cost. The optimization also showed that in general, a lower transfer case ratio was better than a higher one; therefore, the transfer case ratio was changed.

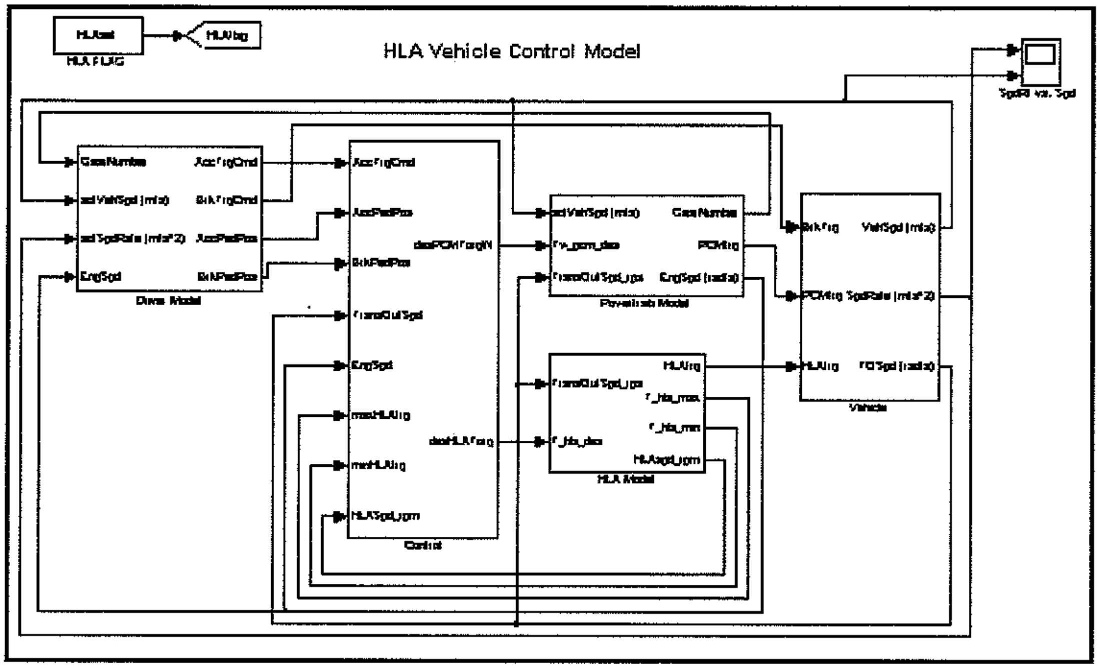


Figure 3: HLA System / vehicle model used to optimize the HLA system.

Packaging

Significant improvements were made to the packaging of the HLA System in the vehicle. The improvements can be summarized in the following points:

- The transfer case housing was redesigned to allow the pump/motor to mount directly to it, thereby eliminating the separate mounting brackets, extra shaft, alignment issues, and reducing the overall assembly length.
- The transfer case / pump/motor assembly was oriented vertically above the driveline placing the pump/motor between the truck frame rails. This leaves more external frame rail area available for the mounting of other necessary equipment, such as the refuse body and associated apparatus. It also puts the pump/motor in a protected position and more effectively blocks noise coming from the pump/motor.
- The fluid conveyance was reduced from 24 ft. of hose and dozens of connections on the concept prototype, to 9 feet of hose and 6 connection points. This improvement was possible because of the reduced number of accumulators and improved placement of components.
- The system oil filter was reduced from two separately mounted filters to one filter manifold integrated with the pump.
- The high-pressure accumulator was moved to a position behind the fuel tank, thereby sharing that space on the frame rail.

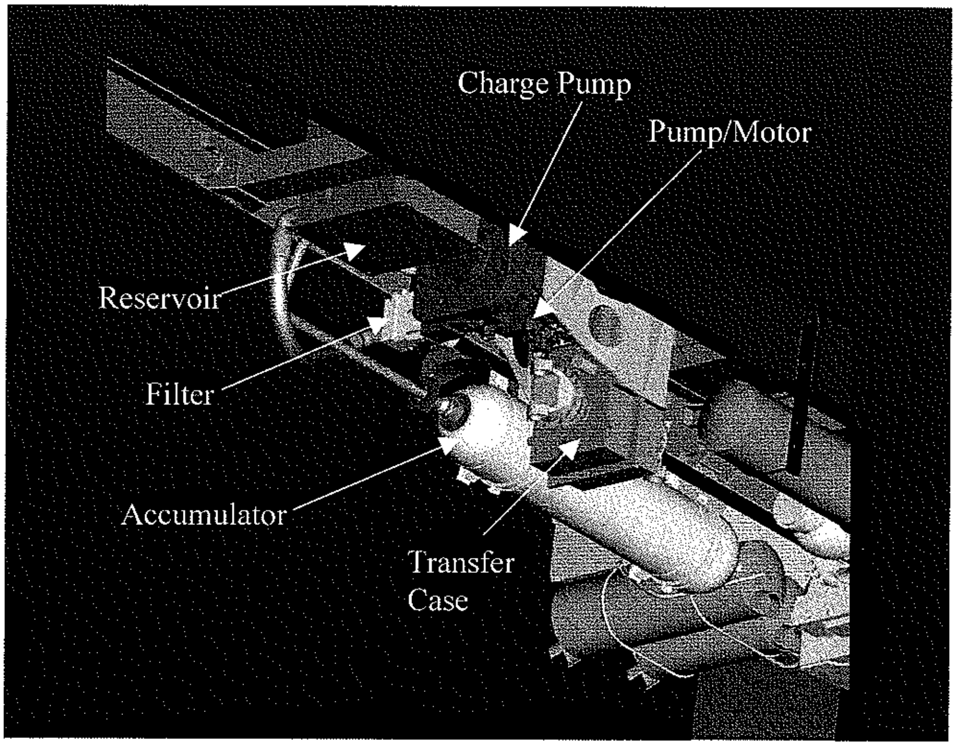


Figure 4: Updated HLA System design installed in a truck.

Open System

The HLA system targeted for refuse trucks was changed to an "open system" design, which includes an oil reservoir open to atmospheric pressure. An open system allows the system to be serviced safely without the need for special tools. The open system also reduces cost and space requirements by eliminating the need for low-pressure accumulators.

Charge Pump

The open system design requires an additional component called a charge pump to supercharge the main pump/motor. An impeller style pump concept was chosen for the charge pump design because its pressure and flow characteristics matched the fill requirements of the piston pump in an acceptable size envelope.

Since Eaton has limited expertise in centrifugal pump design, this design was outsourced to a company specializing in turbo machinery design. The vendor designed impeller and volute geometry to meet Eaton's requirements for the HLA System. Eaton subsequently designed this geometry into the HLA System so that the charge pump became an integral part of the pump/motor. This integration improves the efficiency and packaging space requirements of the HLA System.

Reservoir

Another component that was added as part of the open system design is the reservoir. The reservoir has rigid design constraints, primarily small size and high flow rates. Computer modeling and lab testing was performed to verify the design of internal reservoir parts would meet the flow requirements.

Pump/Motor

The pump/motor design was improved in several ways. The new pump housing made of aluminum was designed to replace the concept cast iron housing. The new housing is lower cost and about 70 lbs lighter. The designs of several internal parts, such as shift pistons, barrel, and a sensor connection were changed to increase their performance and reliability and reduce manufacturing costs.

Transfer Case

The main upgrade to the transfer case was the addition of direct pump mounting capability. This eliminates the need for the expensive and space-consuming separate mounting that was used on the concept prototype. As was already mentioned, the transfer case gear ratio was changed as part of the overall system optimization.

The transfer case contains an internal clutch. The clutch design was improved so that clutch engagements and disengagements are repeatable and robust. Transfer case bearings were also upgraded to provide longer life and reliability.

Filter Manifold

The concept filter manifolds were mounted in-line with the hoses. This created the need for extra hose assemblies, space and leak points. A new filter manifold was designed, which is integrated with the pump. This design eliminates the need for an entire hose assembly. The new filter manifold includes a pressure regulating valve which was specifically tuned to balance the trade off of pressure drop and filtration capability.

Sensors

There are multiple sensors used in the HLA system. Most of the sensors were upgraded to models with lower costs or higher reliability. A few new sensors were added to improve system fault diagnosis.

Noise

The current US EPA drive-by noise regulation requires that a truck's overall noise level does not exceed 80 dBA at a distance of 50 ft. In order to help a vehicle meet that requirement, the HLA system needs to emit much less noise that the truck so that the product is a 'non-contributor'.

The main sources of noise in the HLA system come from the pump/motor and transfer case. Significant analysis and design work went into reducing noise emissions coming from the pump/motor. Stiffening the new aluminum housing in key areas and modifying internal pumping parts have helped to control the noise produced by the pump.

Design improvements were also included in the transfer case design. Proper gear profile tolerances were chosen that are expected to keep the transfer case noise within acceptable limits.

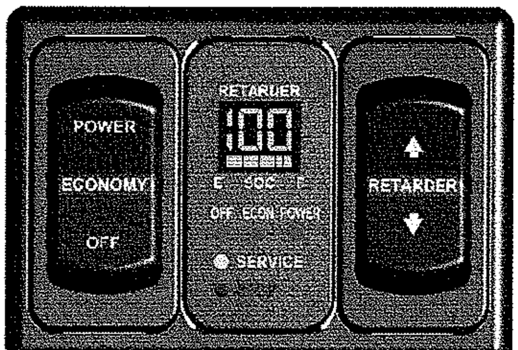
Software

Numerous improvements were made to the diagnostic and control functionality of the system software. The most significant changes are listed below.

- The overall structure of the software was simplified and streamlined. Redundant tests were removed while making sure all the known causes of faults are addressed and each fault is unique. More test conditions were added, but the overall size and complexity went down.
- The transfer case control logic was modified to improve fault detection and safety.
- Auto-calibration and temperature compensation algorithms were added to maximize the HLA System's performance across varied operating conditions.
- Electronic and controls integration with the vehicle has been improved resulting in smoother operation and better braking feel.
- A retarder function was added to the braking function.

User Interface

HLA System specific switches and displays were designed and integrated into the control system. This interface will be located on the dashboard and will work on the vehicle's existing data bus. They allow user control and configuration of the HLA System's operating modes. Depending on end user feedback, this interface may or may not be included in production vehicles.



Product Assurance

The HLA team has performed many activities that fall under the category of "product assurance." Product assurance is any activity that works to the goal of demonstrating the confidence the product will perform as expected in the field. Tools used for the HLA system include:

- System function failure mode and effects analysis (FMEA)
- Use/misuse FMEA
- Hazard analysis
- Component design failure mode and effects analysis (DFMEA).

The system function FMEA is a systematic tool for analyzing how each of the system functions of the HLA system could potentially fail. A risk priority is assigned to every failure mode. One of the primary functions of the HLA system is to provide torque when the driver commands vehicle acceleration. The system function FMEA asks the question "how can this function fail." One failure mode for this case is that the HLA system would be unable to provide torque. All the possible root causes for this failure would be listed. Each failure is rated on severity, occurrence and detection scales. These rates are combined mathematically to determine risk. Actions are taken for any items that may be safety related or have been identified as high risk. In actuality, any failure mode that can be reasonably avoided or mitigated is addressed.

The use/misuse FMEA is similar to the system function FMEA. This FMEA focuses on the everyday uses and misuses of the product by the end-user. Examples would be driving habits, typical maintenance procedures, end-of-life procedures, vandalism, acts of nature, etc. This analysis forces the designers to consider everyday events. This analysis brings a new perspective to the design requirements.

The hazard analysis reviews the design to determine what hazards that the HLA system may present given an outside trigger event. For example, in a collision, what hazards could the HLA system create? The hazard analysis focuses on safety related items. All safety items are reviewed to determine how they can be avoided or mitigated.

Finally, component DFMEAs have been performed on all the subsystems of the HLA system. This is the very common design tool. At this level, every part is examined for function and how it can fail. From this analysis actions are identified to eliminate the failure modes if possible. Also, this analysis gives insight to the tests that should be performed to validate the design. Because failure modes are identified, the test for stressing those failure modes can be created.

The HLA program team has been very rigorous in the application product assurance activities.

Conclusion

The HLA System has been redesigned and optimized for application in heavy-duty refuse collection vehicles. The new design includes many improvements over the concept design. These improvements include:

- Better packaging in the vehicle resulting in easier installation and more efficient use of space.
- Increased reliability and safety.
- Improved vehicle performance and driving feel.
- Better serviceability.