Aftermarket Hydraulic Regenerative Braking System

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Abstract
In this summary, an aftermarket regenerative braking system is described. Patent and market research shows that the design and development of an efficient after market regenerative braking system could be a competitive short term solution to the need for more fuel efficient vehicles. New hybrid vehicles improve in efficiency with each generation, but they remain an expensive and long term solution. An aftermarket system could increase fuel efficiency without the purchase of a new vehicle or substantial changes to the national infrastructure. The target market for this design will be taxi cabs operating within an urban setting. The following report details the baseline design of an aftermarket hydraulic regenerative braking system for a 2007 Ford Crown Victoria and proof of concept through a working test fixture. The system is designed to capture energy from the vehicle’s driveshaft upon braking, store energy in the form of compressed nitrogen gas, and release energy back to the driveshaft to accelerate the vehicle. The system is designed to accelerate the vehicle from 0-9 mph without use of the internal combustion engine. During this capstone phase, a test fixture was designed and all parts were selected. Unfortunately, due to financial issues, a physical proof of concept was not constructed.

Figure1: Full scale model with one possible orientation for major system components
The Need for Project

There is a need for an aftermarket regenerative braking system (RBS) to increase fuel efficiency in vehicles already on the road. Dependence on automobiles and increased concern about global climate change has created the need for more fuel efficient vehicles. One common method to increase fuel efficiency is the incorporation of a regenerative braking system (RBS) into the vehicle. This allows for the capture of energy normally dissipated as heat during braking, which is used to propel the vehicle at a later time. Unfortunately, these systems are only available on new hybrid vehicles. The development of an aftermarket RBS would allow for increased fuel efficiency in vehicles already on the road. Such a system would have a quicker impact at a lower cost than the purchase of a new hybrid vehicle.

The Design Project Objectives and Requirements

The objective of this project is to design an aftermarket hydraulic RBS unit that will accelerate a taxi cab from 0-9 mph without use of the internal combustion engine. The design will be proven through a working test fixture.

Design Objectives

The objectives of this project are to design a full scale aftermarket hydraulic RBS and prove the concept through a test fixture. The system is designed for a Ford Crown Victoria, as research shows such a design could have a great impact on the taxi cab market (Rep 3). The design must not complicate normal vehicle use and the installation shall not require significant changes to the vehicle’s drive train. The design’s cost must be substantially less than a new hybrid vehicle. A working test fixture must be built to prove the efficiency of the full scale system.

Design Requirements

The design shall store enough energy during braking to accelerate the 5000lbf vehicle from 0 -9 mph at a rate of 3.08ft/s² (Rep 7.1). To achieve this, the system shall have an efficiency of about 12%. Based on the recent success of hydraulic RBSs in the refuse truck industry and their potential for retrofitability, the design will utilize a hydraulic system. For safety purposes, the working pressure of the system shall be less than 4500psi (Rep 7).

Design Concepts considered

Three different mounting schemes were considered for the hydraulic system. The fundamental components required for a hydraulic RBS include: pump, hydraulic motor, accumulator, reservoir, and associated valves, fittings, tubing and oil. Each of these components can be sized by calculating the energy required from the hydraulic motor to meet the
stated design requirements.

In-Wheel Concept

An in-wheel design would ideally mount all of the fundamental components inside of a wheel (Figure 2). This concept is desirable in terms of the system being retrofittable. The four tires would be sold and installation would be as simple as changing the tires. Unfortunately, upon further research, wheel balance became a major problem since hydraulic fluid is constantly flowing in and out of the reservoir. Also, at least a one gallon accumulator would be required to have a reasonable impact on energy savings. As a compromise, it was considered to mount the accumulator and reservoir elsewhere in the vehicle and to mount the pump and motor inside of the wheels. This does not solve the wheel balance issue and adds an issue of heat dissipation, steering, and how to mount hydraulic lines. (Rep 7.2)

Modified Differential Concept

This concept considered replacing or modifying the vehicle’s differential. Instead of the standard single driveshaft input the differential would be re-designed to accept a second input shaft driven by the hydraulic motor (Figure 3). The addition of the second input shaft would require precision made gears and components in order to maintain the functionality of the differential. This remains to be an intriguing idea; however in terms of an undergraduate project it carries many risks. It would most likely exceed any budgetary restrictions and require outsourcing of custom made parts.

Parallel Shaft Concept

With this concept, pump and hydraulic motor shafts would be mounted parallel to the vehicle’s driveshaft and connected via timing belt and chain driven assemblies (Figure 4). The space around the vehicle’s driveshaft near the differential in a rear wheel drive car is enough to mount the pump and motor. A desirable option would be to create custom mounts for the system which bolt into the differential casing. In addition, the proximity to the trunk would allow the accumulator and reservoir to be mounted in unused trunk space such as the narrow shelves or side cutouts over the wheel wells.
Recommended Design Concept

A test fixture was designed to simulate the full-scale parallel shaft aftermarket RBS.

The parallel shaft concept was determined to be the most desirable for this project. There is ample room on either side of the differential in most passenger vehicles. Also, the standard bolt pattern on differential cases allows for a fixed contact location suitable for mounting the pump and hydraulic motor. A fixed gear ratio belt and chain driven parallel shaft concept was chosen as the transmission system.

Design Descriptions

It would be unfeasible to incorporate this early prototype into an operational passenger vehicle. Instead, a tabletop test fixture was designed in parallel with the full scale system to test efficiency and feasibility. The test fixture design incorporates a full scale pump, hydraulic motor, accumulator and reservoir. A 3-phase, 10hp electric motor and a test shaft will take the place of the vehicle’s ICE and driveshaft. During testing, the electric motor simulates stop-and-go cycles by spinning the test shaft with the same torque and rotational speed of a vehicle’s driveshaft as calculated from the EPA urban dynamometer driving schedule (Rep 2.1.4).

The first objective of the RBS is to capture energy using a hydraulic pump to displace fluid from a reservoir to an accumulator (Figure 5). This process is the same for the full scale system and the test fixture. A timing belt and pulley system with a 3:1 gear ratio couples the shaft to the hydraulic pump. The gear ratio was chosen to optimize fluid flow so that the pump is most efficient. This places the pump’s operational range between 46mph to 11mph. When the vehicle brakes during this range, a solenoid operated valve directs up to one gallon of hydraulic oil into a high pressure piston accumulator pre-charged to 1300 psi (Figure 6). The resistance from the pump shaft helps to brake the car. Any additional desired braking force would be dissipated by the caliper brakes on the vehicle (the electric motor’s braking system during testing).

To complete the system cycle, the energy stored in the accumulator must be released through the hydraulic motor to perform a launch (Figure 7). Due to the high torque required at the driveshaft to overcome the static friction of the vehicle, a 2:1 chain and sprocket system couples the hydraulic motor to the shaft. This system is
identical between the full scale and the driveshaft, but the resistive force on the driveshaft caused by the mass of the car and friction will be recreated using the electric motor’s dynamic braking feature.

Since the hydraulic pump and motor are mechanically attached to the driveshaft, the pump cycles fluid in a loop to a low pressure reservoir to reduce resistance when driving. The hydraulic motor is attached via an overrunning clutch which disengages the motor shaft from the system whenever the driveshaft speed is greater than the motor shaft speed (Rep 9.2). The belt and chain systems on the test fixture will be enclosed within a 23.5” X 22” X 11.25” aluminum box for safety. An encoder mounted on the test shaft will be wired to a DAQ and record velocity data throughout the test.

**Analytical Investigation**

Based on the operating range of the hydraulic pump (4800 to 1200 rpm) a vehicle stopping from 46mph will displace 0.43 gallons of oil to the accumulator, pre-charged with nitrogen gas to a pressure of 1300 psi. At this pressure, the pump operating in braking mode would cause a 5000 pound vehicle to decelerate at an average rate of 4.37 ft/s². For the selected commercially available hydraulic motor, one complete launch will be defined as accelerating the vehicle from 0-9 mph at a rate of 3.08 ft/s². To achieve this, the hydraulic motor must transmit a torque of 195 ft-lbs to the driveshaft, attaining a maximum speed of 296 rpm. The selected hydraulic motor displaces 15GPM. At this rate, 0.75 gallons of fluid must be released from the accumulator through the hydraulic motor at a pressure of 1300 psi to attain a successful launch.

**Key Advantages of Recommended Concept**

The key advantages to the parallel driveshaft concept includes its minimal impact to standard vehicle operation, ability to be simulated with many off the shelf components in a lab setting, and its potential for retrofitability. This design avoids the problems associated with wheel balance for an in-wheel design and has the added benefit of being located close to the trunk. The accumulator and reservoir can be mounted in the trunk. It is a simple task for any mechanic to run tubing through a hole drilled into the underside of the trunk which can then be sealed with a plug. The remaining installation would be a system bolted to existing hole patterns on the differential casing.
(varies per car model). The test fixture for this design was much less complicated than the modified differential concept, and considering the cost of replacing the differential and machining precision components, the parallel shaft idea had the most potential to remain a cost-effective solution in the case that the design went into mass production.

Financial Issues

The cost of the test fixture for this design placed it on the high end of Capstone projects. The cost associated with building the test fixture for this project was substantial due to the high pressure, torque and operating speed of the system as well as the safety considerations associated with these requirements. A great deal of attention was given to minimizing cost, finding competitive quotes, and designing around commercially available parts. Even with the majority of electrical components donated, the tabletop test fixture built with commercially available components would cost $6861, plus the cost of machining. About $2000 of this cost is only associated with powering and controlling the test fixture and would not carry into a prototype design incorporated into a vehicle. Unfortunately, due to budget restrictions, the test fixture was not constructed during this capstone rotation. An estimated rate of return for a full scale design was found to be between one and three years (Rep 8.7).

Recommended Improvements

Construct test fixture, perform optimization and mechanical life test analysis and focus on full scale design. Given more time and access to vehicle specifications, the full scale design should be developed more thoroughly, with analysis to consider system vibration under harsh road conditions. It is important to analyze all mechanical connections to ensure they can withstand a reasonable life test. In addition, an algorithm could be developed to properly size all mounting plates and components by inputting the model type of the vehicle to be retrofitted. Detailed installation instructions can be developed and optimization analysis could be performed to find the ideal fluid volumes and pressures, whereas this project gave priority to cost savings and lab safety concerns. Most importantly, the control systems should be designed to ensure flawless interaction between the RBS and the current vehicle system with minimal input by the operator.