

Measured Power Dissipation of Shock Absorbers on Light and Heavy Commercial Vehicles

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ABSTRACT

Vehicle shock absorbers are designed to dissipate kinetic energy through frictional viscous forces. In some circumstances, this can be in the order of kilowatts of instantaneous power dissipation. This study quantitatively assesses the vehicle damper system energy dissipation of a low-mass utility vehicle and a high-mass hauling vehicle, using empirically derived regression models of the working dampers and custom data logging equipment. The damper force and power is derived from post-processing of the measurement of critical damper metrics, including linear velocity and temperature. Under typical operating conditions, the low-mass utility vehicle showed an average power dissipation of 39 W for a single shock absorber, and approximately 150 W for a complete vehicle-damper model. The high-mass hauling vehicle demonstrated an average power dissipation of 102 W for a single shock absorber, and approximately 600 W for a complete vehicle-damper model under laden operating conditions. Our results provide evidence of the amount of energy available for harvesting from a vehicles' damper system using a kinetic energy recovery device.

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INTRODUCTION

During travel, a vehicle is subject to excitation from a multitude of impacts, road undulations, acceleration and movement due to driver inputs. Current vehicle shock-absorber systems use viscous dampers, which dampen the severity of the vehicle's motion and improve passenger comfort and vehicle handling. The energy is dissipated through the dampers and wasted as heat. This in-depth study analyses the amount of energy dissipated through a vehicle damper as a feasibility study to implement a kinetic energy recovery device. Previously, theoretical models of vehicle shock absorbers have been employed [1,2,3,4] to determine the kinetic energy dissipation through the vehicle's shock absorber (damper) system, with Kawamoto and Zuo et al. focusing on developing a quantitative experimental analysis of the energy dissipation.

Energy output from the damper system is influenced by road roughness, vehicle speed and vehicle manoeuvres. While analysing highway roughness, Segal and Lu calculated that a typical passenger vehicle travelling at 30 mph (50 km/h) dissipated approximately 200 W [5]. Additionally, theoretical quarter-car models developed by Abouelnour and Hammad suggest that 150 W of electrical power could be generated by the shock absorber of a vehicle travelling at 56 mph (89.6 km/h) [2]. Zuo et al. have developed a half-scale model retrofit damper prototype energy harvester. Their experiments suggest that 16-64 W is achievable from a vehicle shock absorber velocity of 0.25 to 0.5 m/s [4]. Modelling by Shaiju and Mitra

demonstrated a kinetic energy recovery system, which converts mechanical energy to produce compressed air for use in alternate suspension systems [6].

Lacking from much of this published research is an empirical analysis of the energy dissipated by a damper during typical operating conditions, including vehicle speed and load transfer due to cornering, acceleration and braking events. Theoretical models have been implemented to replace the costly exercise of developing an experimental analysis technique. We hypothesised that our experiment would yield 20-200 W of average power dissipation during typical operating conditions of a low-mass utility vehicle. Applying a linear normalised mass-model extrapolation suggested that on average, a heavy-mass hauling vehicle would dissipate 5-7 times this value during typical vehicle operating conditions.

This study aimed to quantify the power dissipated from a vehicle damper to determine the potential for energy harvesting. The harvested energy could be used to increase the fuel efficiency of the vehicle, thus reducing fuel consumption and operator cost. To develop an instantaneous power dissipation response, we designed an experimentation matrix to determine the critical damper metrics to measure. Damper displacement, temperature and velocity were measured using a custom-designed data logging system. These metrics were input into a regression model to determine the damping force response of the system. The model was

developed from dynamometer tests performed on the two working dampers. We calculated the instantaneous power dissipation using the modelled damping force and the measured damper metrics.

METHODS AND MATERIALS

Regression Modeling Each Damper

To develop an accurate model of the power dissipation of the damper, we developed a regression model based on observations of each functioning damper. The model correlates the velocity and temperature of each damper to the force response exerted. Damper dynamometer experiments were performed at varying temperatures to develop a database of sample points, and the temperature, velocity and load cell information output from the dynamometer was collected. To interpret the data from the dynamometer cell, a Matlab script was written to convert the raw data generated into discrete values for further post-processing.

To help develop the regression model, graphical representations were developed to qualitatively and quantitatively validate the behavior of the damper. The images were validated by the manufacturer and compared against factory conditions to confirm accurate measurement, and computational processing was then applied. A surface representation of the damper response to velocity and temperature was developed, as shown in [Figure 1](#).

To generate the model, a close-matching polynomial regression of the damper's force response to velocity at discrete temperature values was applied. An eighth-order polynomial fit, developed through regression analysis in Matlab, produced an acceptable error. The discrete temperature polynomials were used in conjunction with a linear interpolation method to develop the force response of the damper at temperatures between the discrete measurements performed. To validate the accuracy of the regression curve, the original dynamometer load cell data and the calculated force response model were overlaid and an error analysis performed. The total discrepancy between the regression values and the measured values measured was 0.215%. This was the greater of the two values calculated using the "Simpsons method of integration" and "Total sum variation" methods.

Data Acquisition

Data was acquired using a custom-designed data-logging system sampling at 400 Hz. The system used a micro-controller system that saved bit value sensor responses to an SD card in text file format. To capture enough data to validate the experiment, the data-logging system had sufficient battery life to continuously record up to nine days of vehicle operation. No mathematical functions were applied during data collection, and all post-processing was completed during data interpretation. Matlab scripts were implemented to interpret the text file data and perform post-processing mathematical functions.

The sampling frequency was determined by an analysis performed when a vehicle is travelling at 110 km/h, experiencing an average road fluctuation wavelength of 0.4 m. With these parameters, a maximum amplitude base excitation frequency was calculated as 76.25 Hz. After applying the Nyquist theorem, and reducing aliasing effects, 400 Hz was chosen as the linear displacement sampling frequency. To measure the linear displacement of a damper, the data acquisition system used a linear potentiometer with a 10-bit analogue-to-digital converter achieving a resolution of 0.215 mm, and a factory-suggested accuracy of 0.1% full-scale output. Temperature sampling was performed at 100Hz using a PT1000 RTD amplified to achieve a sample resolution of 0.24 °C, and a factory-calibrated accuracy of

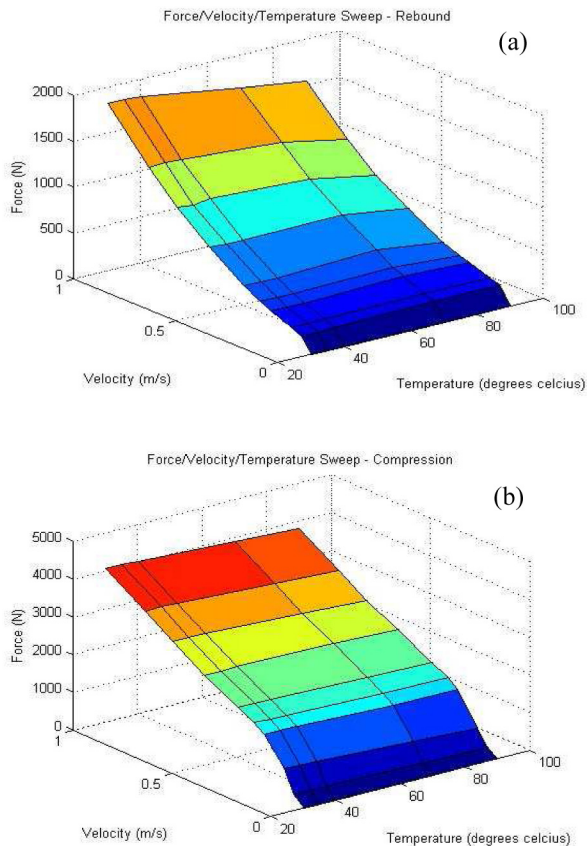


Figure 1. (a) Force, velocity and temperature response of the tested damper in rebound (extension) (b) Force, velocity and temperature response of the tested damper in compression

0.5% full-scale output. To further improve the validity and knowledge of the routes taken, GPS data was collected. This included altitude, speed, and GPS time and geographical coordinates at a frequency of 2 Hz.

Vehicle Details

The test vehicles were a low-mass utility vehicle and a heavy-mass hauling vehicle.

Low-Mass Utility Vehicle

The low-mass utility vehicle was a 2005 Toyota Hilux SR5, with a curb mass of 1800 kg and legal gross vehicle mass of 2810 kg. The four-wheeled Hilux suspends vehicle motion due to excitation using a live rear axle with semi-elliptical leaf springs and individual wheel dampers. For this test, the data logging damper was located on the left rear corner as shown in Figure 2, and the data logging box was fastened to the left rear wheel arch within the rear tray of the vehicle. This vehicle suspension system will have natural damping due to the coulomb sliding friction between the leaf spring flat plates. However, as this study aimed to quantitatively analyze the power dissipation of a vehicle damper, the damping value of the spring system can be ignored, because an energy-harvesting damper would not recover this energy.



Figure 2. Toyota Hilux data logging damper and the position potentiometer attached to the left rear wheel

Heavy-Mass Hauling Vehicle

The heavy-mass vehicle was a 1997 Freightliner FL112 flat-bed hauling vehicle with a legal gross vehicle mass of 26,600 kg, as shown in Figure 3. The maximum legal weight distribution split of the heavy vehicle is 65 % rear axle weight, as given by factory specifications. The suspension system is a trailing-arm live rear axle with individual wheel dampers and adjustable height-level-controlled air springs. As for the Hilux, the heavy-mass vehicle data logging damper was located on the rear left wheel.



Figure 3. Heavy vehicle tested: a 1997 Freightliner FL112

Road Type

Road types were classified into categories based on a qualitative analysis of GPS recordings taken from the vehicle during operation in the region of Newcastle, Australia. The definitions of road types are given in Table 1.

Table 1. Road type qualitative definitions

Road Type	Description
Rural	Sealed road, however no curbing or distinct lane separation techniques applied. Maintained less frequently than suburban and highway roads.
Suburban	Typical sealed suburban road with curbing. Typically two lanes, one servicing each direction.
Highway	Equivalent to a controlled-access highway. Multi-lane dual carriageway, well sealed and maintained frequently.

Data Interpretation

To develop an understanding of the damper's behaviour during typical operating conditions, the analysis was performed on a trip-by-trip basis. The data acquisition system was equipped with a three-axis accelerometer and real-time clock. A Matlab script was used to break the collected data into consecutive vehicle trips by interpreting the instantaneous combined acceleration of the vehicle and GPS data. The vehicle's operation during tests was determined by aligning the real-time clock feedback from the microcontroller system and GPS recordings. This enabled a breakdown of each vehicle's collected data into daily sections, where further reduction to individual trips was possible and the vehicle's behaviour and road interactions were fully understood. Time spent while the vehicle was at standstill, "still time", differed markedly between trips and trip types. As a fraction of total trip times, still time was between 6% and 26% for the various trip types. For this reason, still time was excluded from calculations.

Derivation of Instantaneous Power

To derive the instantaneous power dissipation of the vehicles' individual damper systems, the regression model was used in conjunction with the data recorded to develop instantaneous damper velocity and force response. The variables were