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ABSTRACT

This paper explores the performance improvements of a 2013 Ford Mustang Shelby GT500 resulting from changes to the rear axle housing. In previous work, described in [1, 2], the rear axle housing was optimized in order to minimize its weight. It was expected that the decrease in weight would lead to improved fuel economy; in this work, the vehicle was simulated for the EPA highway drive cycle (HWFET) both before and after the optimization of the housing, in order to quantify the changes in fuel economy. It was found that the optimization of the housing did produce a modest improvement in the chassis energy demand and in the fuel energy demand.

Keywords: Automotive axle, Dynamic analysis, Vehicle performance

INTRODUCTION

It is generally known that, if all other factors are held constant, a vehicle with lower mass will have greater fuel economy than one with a greater mass. Therefore, lightweighting of vehicles is of strong interest, both in practical terms and in theoretical studies. There are many approaches to lightweighting, some involving new and innovative materials and others involving new configurations or designs. Yet another approach is to simply optimize existing components in a vehicle, with the goal of reducing them to the minimum mass that will still allow them to satisfy all of the specifications for those components. In previous work, a specific vehicle component, the rear axle housing, was optimized to minimize weight while still meeting stress and deflection constraints, and it was found that the weight could be reduced by 47% [1, 2]. It was stated that the reduction in weight should improve fuel economy; however, that improvement was not quantified in that work. In this work, the vehicle is modeled in Simulink, and the model is run with the EPA highway cycle (HWFET), for both the original vehicle and the vehicle with the optimized rear axle housing.

The paper is organized as follows: in the next section, background is given, including an overview of some of the usage of dynamic modeling for the analysis of different types of vehicles. Next, the equations for the dynamic model are presented, along with details of the implementation in Simulink. The section after that gives the results, followed by a conclusion.

BACKGROUND

Determining the performance of a vehicle, and analyzing the possible effects of changes to the vehicle, is an important part of the development process. With the high expense and time commitment involved in developing prototypes, the use of dynamic models of sufficient fidelity to provide meaningful results will benefit the development process.

Dynamic modeling has been used extensively to analyze vehicle performance. In [3, 4, 5], a dynamic model was used to analyze and determine a control algorithm for a hybrid electric vehicle powertrain. The integration of sensors, actuators, and vehicle dynamics into a single model was presented in [6], with the model used in that case to develop controllers for vehicle safety. In [7], a vehicle configuration with four motorized wheels was analyzed. While the models were of varying complexity, in each case they were able to provide results of sufficient fidelity to provide some degree of confidence in the predicted performance, and to ensure that the vehicle performance would meet the specified criteria. As vehicles increase in complexity, appropriate models are used for a variety of different analysis tasks.

DYNAMIC MODELING

Prior to implementation in MATLAB/Simulink, a mathematical model was developed for the vehicle. This model is based on a simple force balance of the various loads on the vehicle, and is drawn from commonly available information on vehicle modeling.

The propulsion force to move the vehicle forward is the tractive or driving force; it is opposed by various road loads. The various road loads on the vehicle are shown in Fig. 1, taken from [8]. They are the rolling resistance F_{rr}, the aerodynamic drag F_{ad}, and the climbing resistance force F_{hc} (the component of the vehicle's weight acting down the slope). There could also be a force required to accelerate the vehicle, depending on whether or not the velocity is being held constant.

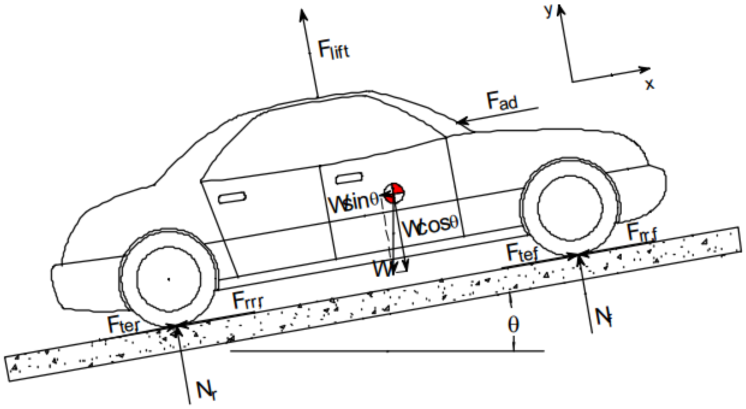

Figure 1: Road Load Reaction Forces [8]

In the absence of acceleration, the road load is given by the equation

$$F_{RL} = F_{rr} + F_{ad} + F_{hc} \tag{1}$$

The rolling resistance depends on the coefficient of rolling friction between the tire and the road, μ_{rr}, and the normal force between the vehicle and the road, which depends on both the vehicle's weight, $m_v g$, and on the road gradient, θ.

$$F_{rr} = \mu_{rr} m_v g \cos\theta \tag{2}$$

The aerodynamic drag depends on air density, ρ; drag coefficient, C_d; frontal area of the vehicle, A_f; and the vehicle speed, v.

$$F_{ad} = \frac{1}{2}\rho C_d A_f v^2 \tag{3}$$

The frontal area of the vehicle can be calculated based on the the height and weight of the vehicle, and is given by

$$A_f = 0.8HW \tag{4}$$

The force due to the road grade is simply the component of the weight that opposes the forward motion of the vehicle:

$$F_{hc} = m_v g \sin\theta \tag{5}$$

Values for vehicle parameters are given in Table 1 [9].

Table 1: Vehicle Parameters [9]

Description	Symbol	Units	Value
Vehicle height, per SAE J1263	H	m	1.392
Vehicle width, per SAE J1263	W	m	1.877
Vehicle length	L	m	4.780
Wheelbase	W_b	m	2.720
Curb weight of the vehicle	W_{curb}	kN	17.132
EPA test weight	W_{test}	kN	1.334
Drag coefficient	C_d	-	0.35
Tire rolling resistance	μ_{rr}	-	0.0125
Engine power	P_{eng}	kW	493.7
Total vehicle mass for original vehicle (corresponding to curb weight plus EPA test weight)	m_v	kg	1882.41
Total vehicle mass for vehicle with optimized rear axle housing	m_{opt}	kg	1873.34
Density of air	ρ	kg/m^3	1.225
Frontal area of vehicle	A_f	m^2	2.090

The power required by the vehicle at any point in the drive cycle can be found once the tractive force is found, by multiplying force and velocity of the vehicle. However, this does not correspond to the power output of the engine, due to various losses in the system. While detailed models can be developed for all of the components in the system, in this analysis the losses were assumed to take on typical values for vehicles of this type. The typical losses for a vehicle are shown in Fig. 2, taken from [10].

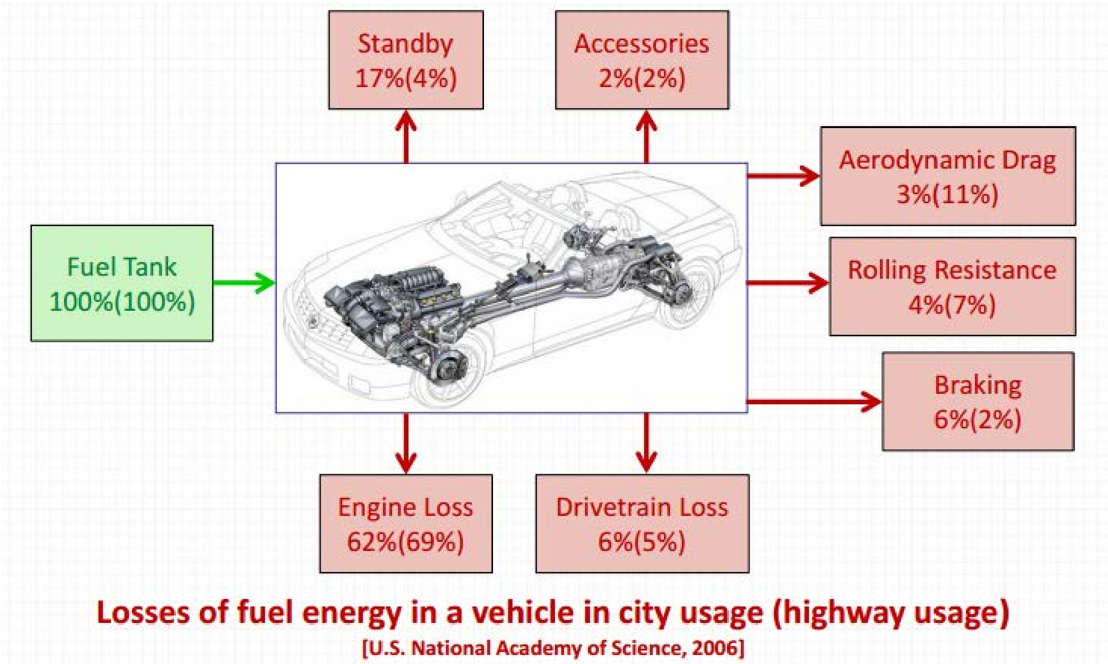

Figure 2: Typical Vehicle Losses [10]

In this analysis, it was assumed that there is no grade, i.e., $\theta = 0$, which eliminates the force due to road grade from the equations. It is also assumed that the drive cycle used is the EPA highway cycle, shown in Fig 3 [11].

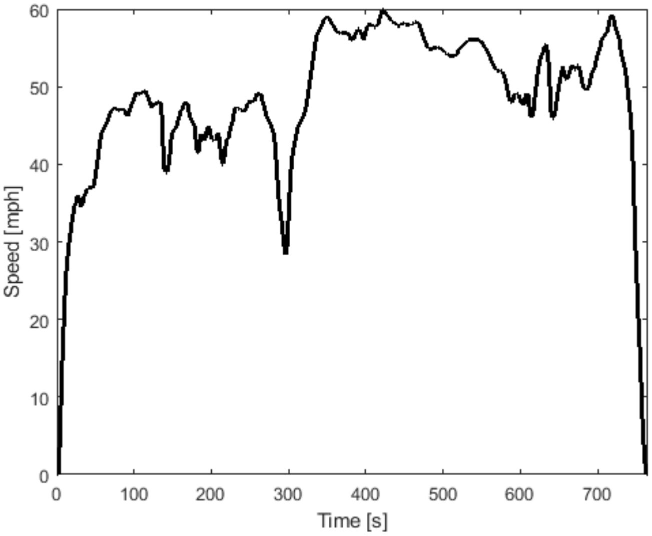

Figure 3: EPA Highway Drive Cycle [11]

Two Simulink models were created, one for the chassis power and energy demand and one for the fuel demand, based on the mathematical model that was developed. These are shown in Fig. 4 and Fig. 5, respectively.

In the development of the model for fuel demand, the efficiency of the internal combustion engine must be considered. Again, it is possible to develop highly complex models for various types of applications. For this application, a simple model was used which considers the various efficiencies of the engine and powertrain. The engine is assumed to have a constant efficiency of 35%, and the axle and transmission efficiencies are assumed to be 95% efficient, with these values taken from [8].

These models were run for both the original vehicle parameters and for the vehicle after the optimization of the rear axle housing [2].

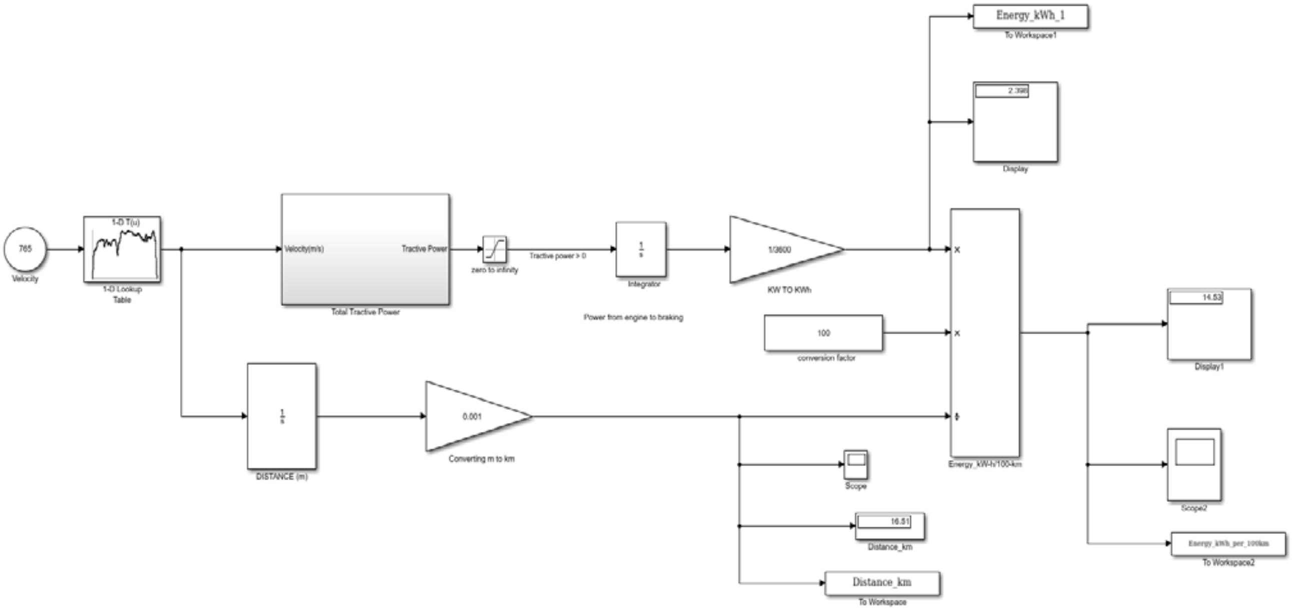

Figure 4: Simulink model for Chassis Power & Energy Demand [2]

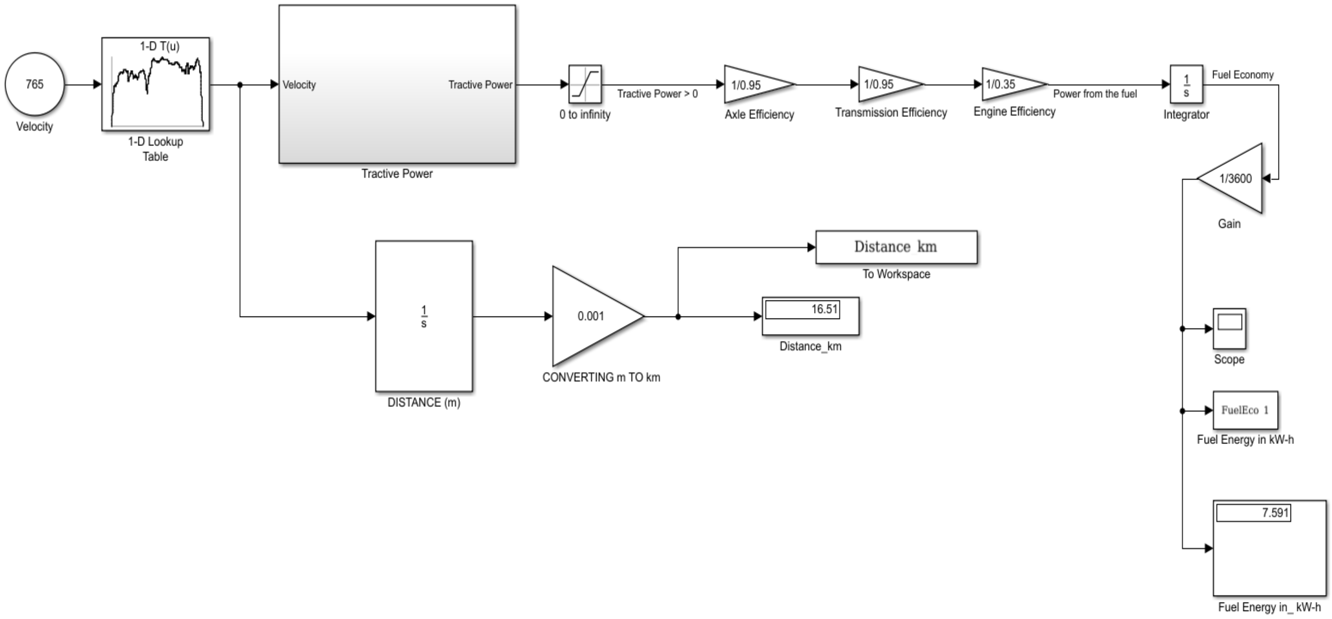

Figure 5: Simulink Model for Fuel Demand [2]

RESULTS

The optimization detailed in [1, 2] resulted in a decrease in weight of 87.8 N, or approximately 20 lb. Over the full drive cycle, this decrease in vehicle weight resulted in a decrease of 6.12% in the chassis energy demand, and a decrease of 1.96% in the fuel demand. This drive cycle is relatively short, however, so a longer trip of 100 km was also considered. For this longer trip, there was a decrease of 10% in the chassis energy demand, and a decrease of 3.3% in the total fuel required [2], as shown in Table 2.

The cumulative energy usage and fuel requirement over the full drive cycle are shown in Fig. 6 and Fig. 7, respectively. Each graph is shown in its entirety, followed by a view of only the last 165 seconds, in order to better see the distinction between the curves. It can be seen, in both figures, that there is a small but noticeable difference between the energy demands before and after optimization of the rear axle housing. As expected, the new, lighter rear axle housing does result in a lower demand for energy to move the vehicle, and consequently will provide a fuel savings. The extent of the fuel savings will depend on the length and type of the trip, with longer trips showing a greater fuel savings.

Even with the relatively short trip corresponding to the highway drive cycle, however, there is a noticeable savings in the fuel required for the vehicle.

Table 2: Simulation Results for Original and Optimized Designs

Description	**Energy Demand for Drive Cycle (kWh)**	**Energy Demand for 100 km trip (kWh)**	**% Change for 100 km Trip**
Chassis Energy Demand before optimization of rear axle housing	2.45	15.0	10%
Chassis Energy Demand after optimization of rear axle housing	2.30	13.5	
Fuel Energy Demand before optimization of rear axle housing	7.65	46.5	3.3%
Fuel Energy Demand after optimization of rear axle housing	7.50	45.0	

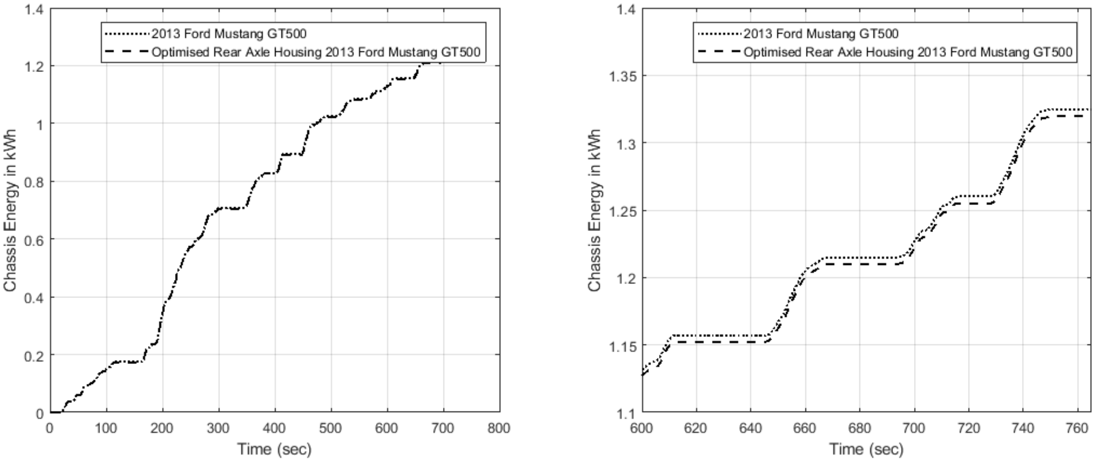

Figure 6: Chassis Energy Demand for EPA Highway Drive Cycle [2]

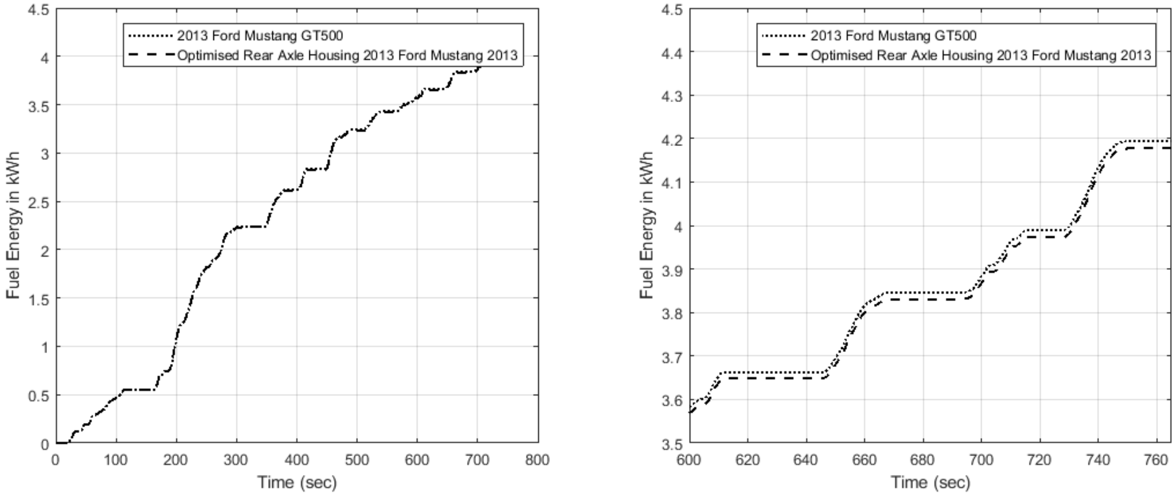

Figure 7: Fuel Energy Demand for EPA Highway Drive Cycle [2]

CONCLUSION

In previous work, described in [1], an optimization was carried out in order to reduce the weight of a rear axle housing on a vehicle. It was expected that the reduced weight would result in a fuel savings for the vehicle, compared to the original design. Based on dynamic modeling and simulation of the vehicle, the expected fuel savings was seen. While the decrease in fuel usage is relatively modest, with a 3.3% reduction in fuel usage for a 100-km trip, this small reduction over a long period of operation for the automobile will result in substantial fuel savings.

The fuel savings indicated by the modeling and simulation result from a single optimized component, the rear axle housing. Automobiles include many other components, however, which may be suitable targets for a similar optimization; such an approach could result in a substantially lower fuel demand, due to the effect of many small improvements.

In addition, experimental validation should be carried out. The vehicle model developed in this paper has not been validated; ensuring that the model is, in fact, an accurate predictor for the actual system. This experimental validation should consist of two stages. In the first stage, the work carried out in [1, 2] should be validated, ensuring that the optimized design will in fact meet the criteria for the component. In the second stage, the dynamic model described in this paper should be validated, through comparisons of these results and the output of the model. Such a validation would provide an additional degree of confidence in the model output, and would allow the model developed in this paper to be used for development of the critical aspects of the project.

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