An Extended Driving Simulator Used to Motivate Analysis of Automobile Fuel Economy

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Abstract

In a senior undergraduate/introductory graduate level interdisciplinary course in energy utilization at Thayer School, students experiment with “driving” a simulated car in different styles and measuring fuel economy. To enable this, we modified an open-source automobile racing computer game to include a realistic model of fuel consumption. After students compared fuel economy calculations to results from driving tests, we challenged them to perform additional analysis of fuel-saving driving strategies in preparation for a fuel economy competition, which culminated in an entertaining public tournament and demonstration. The goal of the exercise was to improve students’ understanding of efficiency considerations in vehicle engineering, including seeing how these considerations apply in different situations on simulated roadways. The driving simulator, via three-dimensional graphics and a user interface with a steering wheel and pedals, provides students with a compelling immersive experience. The framework of striving for minimum fuel consumption (popularly termed “hypermiling”) engages students’ attention as they try to improve their own driving performance and compete with each other, and gives them an incentive to consider subtleties of vehicle power requirements, engine efficiency maps, and their interactions. Compared to experiments with real vehicles, the simulator ensures student (and bystander) safety, allows precise display of fuel consumption rate and total fuel consumption, allows more precisely repeatable experiments, enables easier interaction between student groups and between students and instructors, and allows experiments with driving styles that might not be acceptable on public roadways. The paper describes the technical development of the simulator, the class activities developed making use of it, and the educational impact of the project.

Introduction

Students are often most familiar with automobiles through the direct experience of driving them. Connecting study of vehicle efficiency to this experience helps to motivate students and to build more complete understanding. But class experiments including driving automobiles would pose serious logistical and safety problems. To provide students with such an educational experience without these difficulties, we modified an open-source automobile racing computer game, *The Open Race Car Simulator* (TORCS) [1], to include a realistic model of fuel consumption. The driving simulator, via three-dimensional graphics and a user interface with a steering wheel and pedals, provides students with a compelling immersive experience. Compared to experiments with real vehicles, the simulator ensures student (and bystander) safety, allows precise display of fuel consumption rate and total fuel consumption, allows more precisely repeatable experiments, enables easier interaction between student groups and between students and instructors, and allows experiments with driving styles that might not be acceptable on public roadways.

Students used the simulator in a senior undergraduate/introductory graduate level interdisciplinary course in efficient end-use of energy, and competed to drive defined courses using a minimum amount of fuel. Striving for minimum fuel consumption in real vehicles, popularly termed “hypermiling,” has spawned enthusiast web sites [2], [3] and competitions in which contestants often top 100 mpg [4]. This framework was used to engage students’ attention as they strive to improve their own driving performance and compete with each other, and to give them an incentive to consider subtleties of vehicle power requirements, engine efficiency maps, and their interactions. In this paper, we describe the technical development of the simulator, the activities developed making use of it, and the class in which we used it.

Technical Development of the Simulator

We were very fortunate to be able to start this project with a highly developed open-source driving simulator, TORCS version 1.3.1 [1]. The simulator includes detailed physical models of vehicle dynamics, and provides three-dimensional (3-D) graphical rendering of the driver’s view out the windshield or views from other vantage points. Although control from a keyboard is possible, a controller including a steering wheel and pedals allows better control, and better simulates driving a real vehicle. We used a Logitech MOMO wheel and pedal set. The standard distribution of TORCS includes models of multiple courses—tracks or road courses—and various race cars that the user can select. Version 1.3.1 includes tracking of fuel consumption, and the dashboard includes a fuel gauge. An accurate model of fuel consumption must include a model of the load on the engine and a model of engine efficiency. TORCS accurately models loads, including acceleration, grade, rolling resistance and wind resistance, but does not attempt to accurately model engine efficiency—it simply uses a constant efficiency at any engine operating point, and consumes no fuel during idling. Thus, for our purposes, we needed to add an accurate simulation of engine efficiency. We also increased the resolution of the on-screen fuel gauge, added display of average and instantaneous fuel economy, and added data logging.

We did not attempt to accurately model any specific engine in our engine efficiency model. Rather, we simply aimed to capture the general trends of how engine efficiency varies with torque and RPM in a hypothetical model. We developed a set of equations to calculate torque, fuel consumption, and efficiency as a function of throttle opening and engine speed. We implemented these calculations in MATLAB [3], and used them to generate contour-plot maps of efficiency and torque as well as tabular data.

TORCS can be configured shift gears automatically or manually. The choice of gearing is an important variable in determining fuel economy. We could have met our objectives of having students carefully consider this effect either by having them program the automatic shift points or by having them operate the vehicle in manual mode. We opted to operate in manual mode in order to make the driving experience more engaging.

We modified the TORCS simulation algorithm to model the engine by interpolating the data in the tables generated from the engine model calculations. This modular approach, separating the modeling calculations from the model implementations, allows developing the model calculations easily in an interactive environment without compiling the complete TORCS code, and also enables the system able to accept tabular model data from other sources, such as engine dynamometer tests. In the future, we hope to use data students gather from such tests in the fuel consumption model.

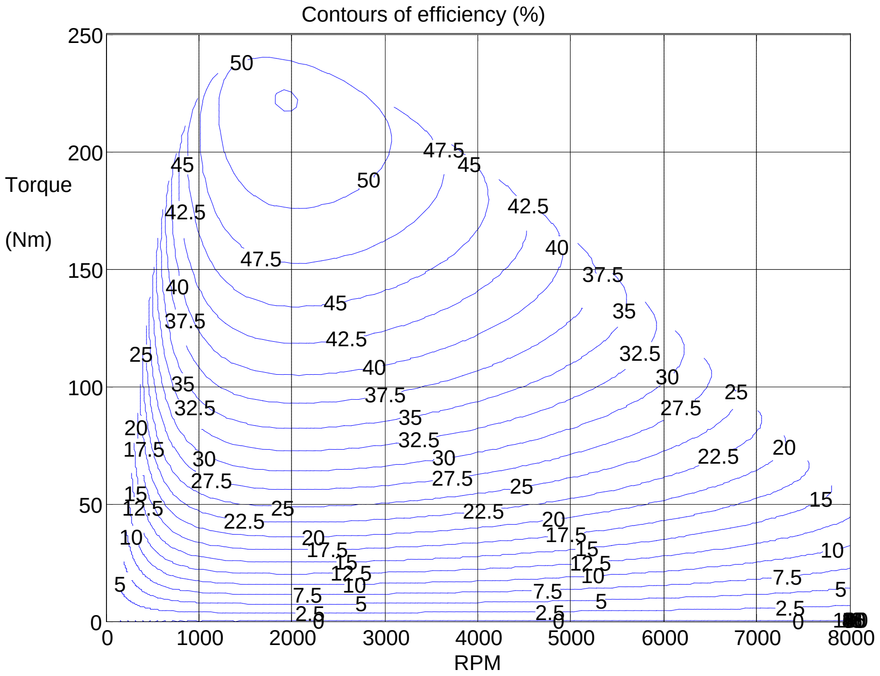

Figure 1. Sample efficiency contours for engine model. The peak efficiency in this particular model is unrealistically high, but the trends are representative.

Efficiency and torque maps used in the first trial of the system are shown in Figure 1 and Figure 2. The peak efficiency, a little over 50%, is unrealistic, but the trends shown are representative. A lower peak efficiency is easy to implement, but we discovered the error after students had begun their assignments with the system, so we did not change it immediately.

The model also includes idle fuel consumption, and a fuel-cut-off mode for coasting with the engine connected to the transmission and turning with the motion of the vehicle, adding drag, but consuming no fuel.

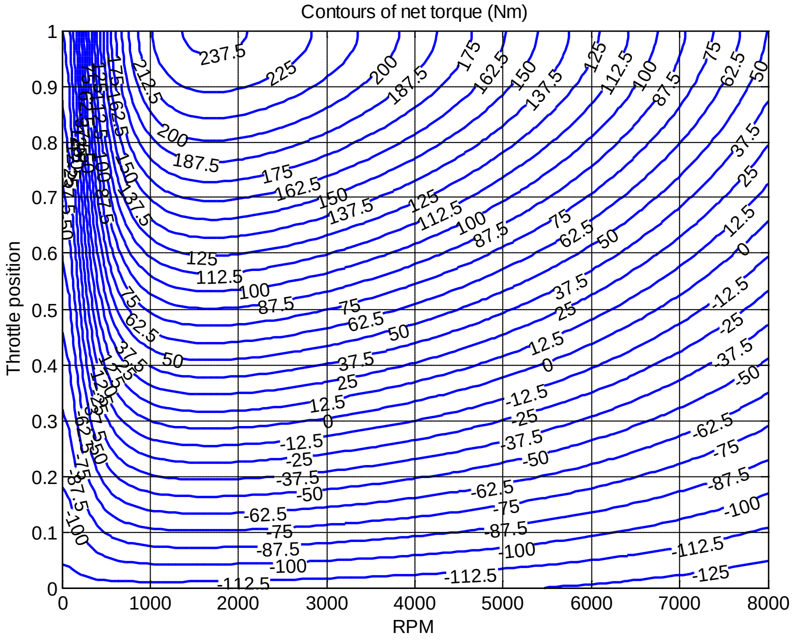

Figure 2. Torque map for engine model

The standard instruments in the driver's dashboard display in TORCS include a speedometer, a tachometer, a bar graph of

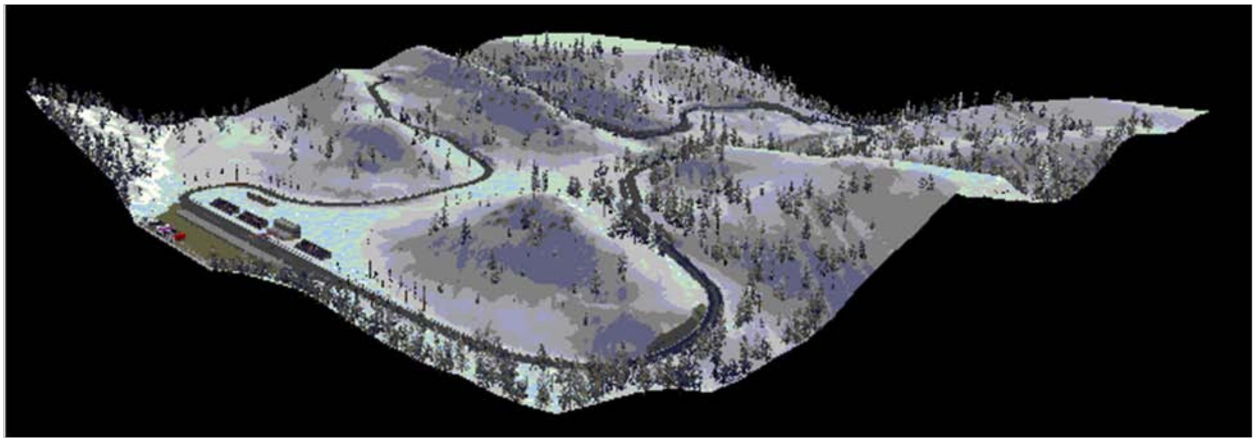

Figure 3. "Alpine 2" course.

throttle position, and a fuel gauge. In addition to increasing the resolution of the fuel gauge, we added instantaneous and average readings of fuel consumption in miles per gallon and liters per km. We also added the capability to output a log file with key parameters such as accelerator position, engine speed, vehicle speed, and fuel level approximately every tenth of a second.

Student Activities and Hypermiling Competition.

Students engaged in a series of exercises leading to increasingly open-ended challenges to develop strategies for a fuel economy competition, which culminated in an entertaining public tournament and demonstration. The goal of the exercises was to improve students' understanding of efficiency considerations in vehicle engineering, including seeing how these considerations apply in different situations on simulated roadways.

Students first analyzed the system based on the engine and load models. We provided model data in graphical and tabular form, as well as providing the code used to calculate the models. The students calculated the combination of steady-state speed and gear ratio that maximized fuel economy, considering the tradeoff between high aerodynamic drag at high speeds and low engine efficiency at low speeds. Next, each student developed a strategy for at least one special situation such as acceleration from a stop, hill climbing, or coasting down hills, where one must select between coasting in gear, using no fuel, or coasting in neutral while idling, using fuel, but avoiding having engine drag slow the vehicle.

Students then tested their theories by driving the simulator in the lab, working alone or in groups of two or three. We chose two courses from the standard TORCS selection: "Street 1," which models mostly city streets with only slight grades, and Alpine 2 which has winding roads over steep hills . Both model roads closed to traffic for a race, with no cross traffic, stop signs, or traffic signals. Thus, the exercise does not model typical driving, but instead is an independently defined challenge. Students first complete both courses driving "normally" without attempting to maximize fuel economy. Results from this run varied widely, with some students using 2.5 to 3.5 times as much fuel as the most economical runs. Because students completed these runs after they studied fuel economy in the class, they may have subconsciously made use of what they learned. In future offerings of the course, we plan to complete this initial test run before any study of fuel economy, so that we truly see the effect of a better understanding.

Next, students drove the flat course attempting to maintain the constant speed that they had calculated would yield maximum fuel economy. This exercise generally confirmed the validity of the calculation, but also underlined how difficult it is to drive a car in the idealized way the calculations assume—even slight grades and slight deceleration and acceleration for corners can have a substantial effect on instantaneous fuel economy.

Finally, we asked students to do their best to complete each course using a minimum amount of fuel, using their best hypermiling strategies. Their fuel consumption in this test was much more tightly clustered than the initial results, indicating that they converged on somewhat similar strategies, but there was still about a 30% spread in each course, keeping the competition interesting.

We invited the groups with the best fuel consumption results, as submitted with the assignment, to participate in a public competition. We also posted the maximum qualifying fuel consumption values, and invited others to join the competition if they could beat those numbers.

For the final competition, we set up two computers connected both to desktop monitors and to large-screen monitors, in a public hall where spectators could congregate and passers-by could pause and watch. Each group had two chances at driving the “Alpine 2” course; only their best run was used to select the best two teams who then competed to drive using minimum fuel on a course they hadn’t seen before. A sportscaster-style narration helped spectators key in on the techniques students were using, and helped them understand the excitement in this sometimes slow-moving competition. A one-minute video of the event on YouTube illustrates the spirit of the event [6].

For such a competition, the use of a simulator was invaluable. It enabled precise comparisons of fuel consumption, and isolated the effect of driver technique, without other random variables such as traffic and weather. It allowed spectators to see and understand what was going on, and allowed multiple teams to drive simultaneously. And it removed any concerns about safety or disrupting traffic. Students could, for example, coast down steep roads at speeds they could barely control, or coast towards the finish line at extremely low speeds that would easily induce road rage on a public highway.

An Interdisciplinary Course in Energy Utilization

As constraints on both energy supply and carbon dioxide emissions become more important, increased energy efficiency will be essential, both to reduce fossil-fuel consumption and to make significant reliance on alternatives feasible. The technologies now in use and under development span the full range of engineering disciplines. Although some of these are addressed well in standard disciplinary courses, high performance for many energy applications requires integration of systems ordinarily developed by engineers from different disciplines. Researchers and entrepreneurs working on improving our society’s energy utilization need to understand the full landscape of challenges and opportunities.

To meet this need, we have introduced a course at the senior undergraduate/introductory graduate level, titled Energy Utilization. The course is designed to be accessible to students with expertise in different engineering disciplines. The learning objectives we chose are listed in Table 1, and the syllabus is outlined in Table 2. Technical issues in efficient systems for energy utilization are analyzed across major uses, with in-depth technical analysis of critical factors determining possible, practical, and economical efficiency improvements in both present technology and potential future developments. Areas addressed include lighting, motors and drive systems, heating, ventilation and air conditioning, transportation, appliances and electronics.

The focus is quantitative technical analysis, not policy or description and evaluation of technical options. The analysis is primarily at a systems level, rather than addressing individual component design. For example, applications of heat exchangers in HVAC (heating, ventilation, and air-conditioning) systems is studied, whereas the design of heat exchangers themselves is already addressed in a course on heat transfer.

In this context, students need to learn about the energy requirements for vehicle propulsion, about the characteristics of internal combustion engines, and about the ways in which these characteristics interface. The driving simulator exercise addresses precisely this combination of issues.

Hybrid electric vehicles are a technology that can be addressed well in this course because of the need for a system level analysis considering the electrical, mechanical, and thermodynamic sub-systems. The driving simulator does not yet include hybrid vehicles. This may be added in the future. For the time being, students in the course analyze much more simplified hybrid vehicle drive cycles using computer code they write themselves.

Table 1. Course Learning Objectives

Students, upon completing this course, are expected to be able to:
1. Express fundamental limits to possible energy efficiency, and evaluate existing or proposed technologies relative to those fundamental limits.
2. Apply first- or second-law efficiency analysis appropriately to a variety of different types of systems.
3. Analyze the first-law or second-law energy efficiency of lighting, drive, HVAC, transportation, refrigeration, appliance, and electronic systems, identifying the loss mechanisms in detail.
4. Perform a system-level simulation of a vehicle or building to evaluate energy efficiency of a proposed configuration.

Table 2. Course Syllabus

1. Introduction and Context
2. HVAC
    a. Thermal envelope; heating and cooling loads
    b. Heat sources
    c. Cooling and humidity control
    d. Ventilation and heat and energy recovery systems.
    e. System-level opportunities: CHP/cogeneration, other heat recovery systems, applications of heat pumps, control improvements, utilization of thermal mass, etc.
3. Transportation
    a. Vehicle power requirements
    b. Vehicle propulsion systems
    c. Transportation system options
4. Appliances and refrigeration
5. Lighting
6. Electric motors and drive systems
7. Electronics

Conclusions

Including a driving experiment and fuel economy competition in class exercises helped focus student attention factors affecting fuel economy, and helped connect course material to real-world applications. Simulations are in some cases inferior substitutes for experiments with physical hardware, but are justified when the physical experiment would not be feasible. However, in this case, the simulation provided additional benefits: more precise measurements and data display, repeatable experiments and fair competitions, and the ability to have the experiment stationary for the convenience of spectators to watch and instructors to assist students.

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