

Introducing the TOP-DOWN-TOP Pedagogy: Systems Thinking that Inspires, Engages, & Promotes Persistence

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Abstract

A new closed-loop educational paradigm is introduced that bespeaks high student engagement through a practically-focused engineering curriculum using as its principle teaching tool a “system of systems” familiar to students. The approach is called TOP-DOWN-TOP (TDT). In each TDT class, students are first presented with a familiar paradigmatic system of systems {TOP}. They then focus down on a subsystem relevant to the class they are taking, learning the principles underpinning its operation {DOWN}. Finally, they return to the overall system to discover how the subsystem just studied works with other subsystems to impact the function of the device {TOP}.

TDT will be taught across several courses in an engineering curriculum tied together by one common overall system studied in each class. This approach allows students to connect theoretical learning to practical systems as well as see how individual courses in the engineering curriculum relate and build upon each other. The recommended ensembled system presented here is an automobile; a complex engineered device with subsystems relevant to every engineering discipline.

A preliminary example of data collection for a TDT Thermodynamics lesson is described. A 2008 Toyota Highlander was augmented with a Tire Pressure Monitoring System. One tire was intentionally deflated to the minimum safe level while the other three remained correctly inflated. The vehicle was then driven on the highway while temperature and pressure for all four tires as well as ambient temperature, pressure, and humidity were collected at regular intervals. Gas mileage was also monitored. These measurements were compared to similar data collected while driving on four correctly-inflated tires. A Thermodynamic model was then developed linking automobile fuel efficiency (a parameter of the overall system) to tire running temperature (a subsystem parameter). The model uses measured tire temperature to correctly predict reduced fuel economy when an automobile subsystem, a tire, is operated away from its specified ideal range.

Keywords

Top-Down-Top, Project-Based Learning, Thermodynamics Education, Automobile, System of Systems

Introduction

Here presented is a new educational approach called TOP-DOWN-TOP (TDT), which reimagines and synthesizes a variety of successful educational techniques to encourage high student motivation and engagement. TDT is a practically-focused, multi-scale engineering curriculum using as its principle teaching tool one paradigmatic “system of systems” familiar to students from their daily experience. TDT’s first unique attribute is a selected system of systems unifying all courses in the TDT curriculum; it appears again and again in each TDT class.

The second unique TDT attribute is its closed-loop approach to presenting the system of systems to students. An automobile is the representative system of systems used here (Figure 1). In each TDT class, students are initially presented with the selected system of systems; an automobile {TOP}. The class then focuses down on a subsystem relevant to the topic, learning the math, science, and engineering principles underpinning its operation {DOWN}. Finally, they return to the whole system of systems (the whole automobile), to discover how the subsystem just detailed works with other subsystems to create a working car {TOP}.

TDT provides more than a theoretical analysis of the automobile and its subsystems. The third unique attribute of this pedagogical method is its hands-on, project-focused, laboratory-based approach to teaching and learning. Students work with a real automobile and its subsystems by instrumenting components, designing and carrying out experiments, and analyzing the resulting data to develop a practical understanding that buttresses and complements classroom theory.

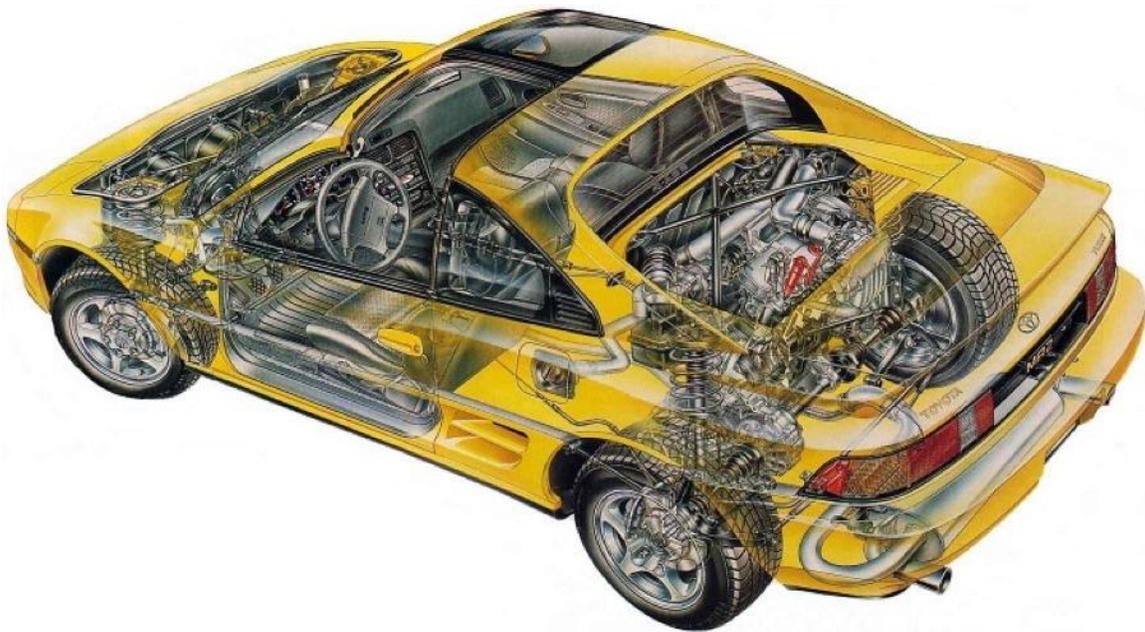


Figure 1: The automobile is a paradigmatic TOP-DOWN-TOP engineered system of systems familiar to students. This image is in the public domain [1].

The educational hypothesis underpinning TDT is that by 1) utilizing as a teaching laboratory a complete, familiar, real-life system [an automobile] that contains many sub-systems {TOP}, 2) identifying subsystems relevant to courses in the curriculum and teaching how those components function via fundamental science and mathematics {DOWN}, and 3) returning to the full scale

system to examine how changes to the subsystem impact performance {TOP}; students experience a high level of confidence and excitement for learning arising from inspiration, engagement, motivation, and persistence. While TDT has not yet been implemented as part of an engineering program, we describe here an example module to showcase how TDT might be practically carried in an engineering course.

Background

Many researchers call for drastic transformation in engineering education to replace traditional, lecture-dominated, and narrowly-focused curricula [2-9]. A new generation of engineers is needed who are technically adept, broadly knowledgeable, flexible, culturally aware, innovative, and entrepreneurial [10]. To increase the effectiveness of education, the National Research Council has recommended that engineering education have components that are hands-on and discovery- and demonstration-based [11]. Students' interest in the subject matter, perception of its usefulness, general desire to achieve, self-confidence and self-esteem, as well as patience and persistence are among the factors that affect motivation [12,13].

Hands-On, Project-Focused, Laboratory-Based Active Learning

A critical component of learning is deliberate practice coupled with targeted feedback; in fact, 'students learn what they practice and only what they practice' [14,15]. Universities have been researching how to meet the transformation demand, and many approaches have been suggested: demonstrative teaching techniques [16], project-based learning [17], competency-based learning [18], collective learning [19], cooperative learning in a classroom environment [20], service learning [21-23], experiential learning [24], distributed project-based learning to address globalization [25-27], learning in a multidisciplinary environment [28], constructivist learning [29,30], and laboratory-based learning [31].

Closed-Loop, Multi-Scale Teaching Shows Sub-Systems' Effect on Overall System

Despite the many transformative education approaches reported, the majority are focused on a traditional bottom-up approach – starting from fundamental science and mathematics and building to the system level. In the conventional paradigm, students are persuaded that they will eventually learn about what really excites them AFTER completing basic and theoretical studies that seem to have no obvious applications. This approach can leave an enormous gap in understanding between engineering theory and its applications [31,32]. Most students never internalize information taught in this style because practical application of knowledge happens too long after it is imparted. Knowledge remains inert unless and until it is “conditionalized” [33,34], that is put into use.

Familiar System of Systems Unifies all TDT courses

In traditional engineering educational programs, students learn about each field separately. This outcome remains true even when utilizing various hands-on pedagogies including project-based learning, lab-based learning, peer perspective learning, team-based learning, multi-modal learning, or discussion-based learning [35-38]. Even Capstone courses, which attempt to tie prior but separate fields together, often cannot convey the complexity of interdisciplinary systems-level thinking if students have not been previously exposed to this approach. Certainly, there exist integrated engineering curricula where different aspects of one unifying paradigmatic system or approach are studied in multiple courses; for example, “Living with the Laboratory” [40],

“Building as a Learning Tool” [41], and “Servant Leadership Projects,” [42]. However, these examples lack the beneficial closed loop and multi-scale attributes central to TDT.

Example Module

A preliminary example lesson illustrating how TDT will be implemented was developed. A dedicated automobile is not yet available to modify and instrument for this purpose. So, a variety of aftermarket sensors easily added to personal vehicles was considered, and an aftermarket Tire Pressure Monitoring System (TPMS) with four external cap pressure / temperature sensors monitored wirelessly by a Vesafe Universal Solar M2 data display was added to a 2008 Toyota Highlander (Figure 2). When TDT is implemented at scale, embedded sensors will likely be more customized, and some data will probably be collected directly from the car’s onboard diagnostic system. Many modern cars have built-in TPMS and automatic gas mileage calculation capabilities, making data collection more facile if a newer model automobile were used.



Figure 2: An aftermarket Tire Pressure Monitoring System (TPMS) was installed on a test vehicle to measure tire temperature when driving with one tire underinflated. Inset A shows the cabin display from which TPMS data were collected while driving. Inset B shows the wireless caps and solar-power receiver before installation. Inset C is a close-up of one TPMS cap installed on a tire’s Schrader valve stem.

The example lesson takes place in an undergraduate Thermodynamics course. As stated previously, the automobile will be introduced as the system of systems being studied {TOP}. While there are many automotive attributes interesting to a Thermodynamics course, this lesson focuses on conversion of gasoline into mechanical power to overcome a variety of friction sources to keep the car moving at the speed desired by the driver. A common measure of car efficacy is gas mileage, the distance traveled per volume of fuel. All other things being equal, a car’s gas mileage is maximized when impeding friction sources are minimized. This lesson focuses on the tires as the automotive subsystem of interest {DOWN} and their friction contribution through rolling resistance. Tires functioning correctly minimize rolling resistance within constraints imposed by their other functions: provision of traction, facilitating vehicle turning, absorbing bumps from road irregularities, etc. Incorrectly underinflated tires impose a higher-than-ideal rolling resistance. Improperly inflated tires deform more as they roll compared to tires at correct pressure. Thermodynamically, extra deformation means the poorly-inflated tire is experiencing extra work done to it by its surroundings, and the tire rubber should therefore increase in internal energy (temperature) above correctly inflated tires. Completing the closed-loop analysis of this system returns to the perspective of the overall automobile and how an underinflated tire impacts its performance {TOP}. Since the under-pressure tire is deforming more, it is absorbing extra energy that would otherwise have gone to propelling the car forward. a car with an underinflated tire therefore experiences poor gas mileage.

Theory

To develop a simple thermodynamic model for the tire's energy transfer processes, the solid portion of the tire is treated as a closed system, shown in Figure 3. The thermal mass of the air within the tire is assumed negligible with respect to the thermal mass of the tire, and energy transfer between tire material and the hub is assumed negligible. In rolling contact, energy is stored during compression then released via relaxation of the elastically deforming tire sections. Due to hysteresis, some of the rolling resistance energy is converted into heat by the viscous nature of the tire rubber [43]. In other words, the process of a tire rolling inputs mechanical power, \dot{W}_{in} , due to hysteresis as the tire deforms and restores its shape at the local road contact point.

The resulting input energy increases the tire's internal energy, $U(T)$, which is a function of temperature only as the tire is a deformable solid. The tire temperature rises until it reaches steady state, the point where heat transferred to the surroundings, \dot{Q}_{out} , offsets mechanical work input. The First Law of Thermodynamics models these energy processes,

$$\frac{dU(T)}{dt} = \dot{W}_{in} - \dot{Q}_{out} = 0 \quad (1)$$

Following Persson et al, the work term becomes the product $\mu_R F'_N v$ where μ_R is the rolling resistance, F'_N is the normal force acting on a single tire (approximately the weight of the car divided by the number of tires) and v is the car's velocity [44]. The heat term becomes the sum of heat transferred from the tire to the air plus from the tire to the ground. Rewriting the First Law in these terms gives

$$\mu_R F'_N v = \alpha_{air} A_{air} (T - T_{air}) + \alpha_{road} A_{road} (T - T_{road}) \quad (2)$$

where α_{air} is the tire-air heat transfer coefficient ($\sim 200 \text{ W/m}^2\text{-K}$), A_{air} and A_{road} are the tire contact area with the air and road respectively, T_{air} and T_{road} are the air and road temperatures, T is the tire temperature, and α_{road} is the tire-road heat transfer coefficient ($\sim 10 \text{ W/m}^2\text{-K}$).

Since $\alpha_{air} > \alpha_{road}$ and $A_{air} \gg A_{road}$, it is reasonable to neglect heat transfer to the road and recast Equation (2) as

$$\frac{\mu_R F'_N v}{\alpha_{air} A_{air}} = T - T_{air} \quad (3)$$

Applying this simple thermodynamic model for a rolling tire to a 5800-pound (25,800 N) 2008 Toyota Highlander driving at 70 miles per hour (31.3 m/s) on the highway with four correctly



Figure 3: A closed system is established upon a car tire, enabling a First Law energy balance. The tire absorbs mechanical power from its surroundings, warms up, and releases heat back to the environment. In steady state, absorbed mechanical power matches outwardly convected thermal power, and the tire's temperature remains fixed.

inflated tires ($A_{air} \approx 0.523 \text{ m}^2$ [45] & $\mu_R \approx 0.011$ [46]) gives $\Delta T = 21.2 \text{ K}$. In other words, in steady state, the tires will register about 20 K hotter than ambient. While the installed TPMS monitoring system does not measure the tire material's temperature directly, temperature measurement of the air inside the tires is taken as a reasonable proxy.

Also of importance for TDT is analyzing Equation (3) in reverse, using measured tire temperature to estimate rolling resistance

$$\mu_R = \frac{\alpha_{air} A_{air}}{F_N v} (T - T_{air}) \quad (4)$$

Thus, the measured elevated tire temperature resulting from an improperly inflated tire can indicate the associated change in tire rolling friction. Since tire rolling friction accounts for between 6.7% (SUV's) and 6.9% (cars) of power consumed on the highway [47], $\dot{E}_{tires} = (0.067)\dot{E}_{suv}$, and Equation (4) can be used to link tire temperature to automobile's energy consumption

$$F_N v (\sum_{i=1}^4 (\mu_R)_i) = \dot{E}_{tires} = (0.067)\dot{E}_{suv} \quad (5)$$

where F_N is the weight of the vehicle equally supported by all four tires. If \dot{E}_{suv} then serves as an inversely proportional proxy for gas mileage, η_{mpg} , then

$$\frac{\dot{E}'_{suv}}{\dot{E}_{suv}} = \frac{\eta_{mpg}}{\eta'_{mpg}} \quad (6)$$

where \dot{E}'_{suv} is the power required to keep the car moving with an underinflated tire ($\dot{E}'_{suv} > \dot{E}_{suv}$), and η'_{mpg} is the fuel economy of the vehicle with an underinflated tire ($\eta'_{mpg} < \eta_{mpg}$).

To put this model into context, consider a Toyota Highlander with properly inflated tires getting 22.5 mpg fuel economy in long-distance highway driving. Its tire temperatures read 21.2 K above ambient, indicating $\mu_R = 0.011$ rolling friction. One of its tires begins running very hot, 31.8 K above ambient [$\mu_R = 0.0165$ per Equation (4)]. The resulting flat tire produces a ratio $\frac{\dot{E}'_{suv}}{\dot{E}_{suv}} = \frac{3 \times 0.011 + 0.0165}{4 \times 0.011} = 0.889$, which gives $\frac{\eta_{mpg}}{\eta'_{mpg}} = 1.125$ and a resulting diminished fuel economy of 20 mpg.

Experiment

As shown in Figure 4, a team member planned a personal trip from Nashville, TN to Gainesville, FL (about 578 miles) and on to Ft. Lauderdale, FL (about 315 miles) the following day. This long-distance drive, completed entirely on highways with few intermittent stops, provided an opportunity for quantitative data collection with the TPMS. Starting in Nashville, one tire was intentionally deflated to the minimum safe level (30 PSI) while the other three were inflated to the

recommended pressure (40 PSI). The vehicle was then driven from Nashville to Gainesville while the temperature and pressure for all four tires were measured via TPMS at regular intervals. Simultaneously, the ambient temperature, pressure, and humidity were collected using a Kestrel 4500 pocket weather station held out the car window and read via Bluetooth-connected laptop inside the car. Gas mileage was obtained by monitoring distance covered and fuel volume at fill-ups. The average result was 20.29 miles-per-gallon. These measurements were compared to similar data collected while driving on four correctly-inflated tires between Gainesville and Fort Lauderdale, FL where the average resulting gas mileage was 23.29 miles per gallon. As a check on fuel consumption validity, the stated highway fuel economy of a 2008 Toyota Highlander is 23 – 25 mpg [47]. Processed data for both trips is given in Table 1.

Results

Processing Table 1 data using the method outlined in the Theory section yields the following rolling resistances for the Gainesville to Ft Lauderdale trip leg (with four fully inflated tires): $\mu_{R,FL} = 0.0109$, $\mu_{R,FR} = 0.0109$, $\mu_{R,RL} = 0.0102$ and $\mu_{R,RR} = 0.0111$. The Nashville to Gainesville trip leg (with the Right Rear tire underinflated) yields the following rolling resistances: $\mu'_{FL} = 0.0109$, $\mu'_{FR} = 0.0109$, $\mu'_{RL} = 0.0110$ and $\mu'_{RR} = 0.0165$. These results produce a power ratio to maintain driving speed at 70 mph between the two tire inflation states of $\frac{\dot{E}'_{suv}}{\dot{E}_{suv}} = \frac{\eta_{mpg}}{\eta'_{mpg}} = 1.1451$. When applied to the 23.29 miles per gallon fuel economy of the fully inflated travel leg, the model predicts fuel economy for the travel leg with the underinflated tire at 20.34 mpg. This result is only 0.24% above the actual measured fuel economy for that part of the trip, 20.29 mpg. Given the model's simplicity, agreement between theory and experiment is surprisingly close. Moreover, if experimental errors were propagated through the calculations (they were not propagated in this analysis), theory and experiment would likely match within experimental uncertainty.

Discussion

In this example, the TDT system of systems that would be presented to students is the automobile. A car was selected because used automobiles are relatively inexpensive compared to educational

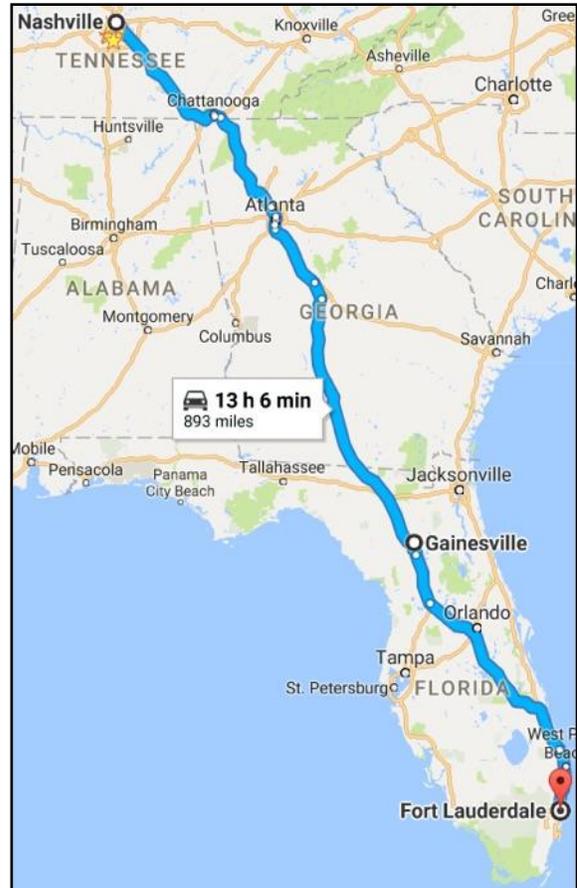


Figure 4: The highway route followed to facilitate TDT data collection totaled ~893 miles with ~578 miles on an underinflated tire followed by ~315 miles on properly inflated tires.

laboratory equipment. Some cost only a few thousand dollars, making them accessible to most engineering programs.

Table 1: Tire temperature and pressure data collected from the TPMS are given along with ambient conditions from the interstate drive. The Front Left (FL), Front Right (FR), and Rear Left (RL) tires were correctly inflated to 40 PSI (2757.9 hPa) at the drive’s start. *On the Nashville-to-Gainesville travel leg, the Rear Right (RR) tire was under-inflated to only 30 PSI (2068.4 hPa), and it was restored to 40 PSI for Gainesville to Ft. Lauderdale leg.

Ambient Temp	Relative Humidity	Ambient Pressure	T _{FL}	P _{FL}	T _{FR}	P _{FR}	T _{RL}	P _{RL}	T _{RR} *	P _{RR} *
[K]	[%]	[hPa]	[K]	[hPa]	[K]	[hPa]	[K]	[hPa]	[K]	[hPa]
Nashville to Gainesville (578 Miles) -- RR Tire Underinflated										
286.2	37.3	999.9	306.9	2757.1	307.9	2895.0	309.9	2895.0	318.9	2068.4
285.9	42.2	998.5	307.3	2826.1	308.9	2963.9	308.0	3032.9	319.0	2137.4
285.7	31.0	993.3	305.9	2826.1	305.4	2963.9	305.9	3032.9	317.9	2137.4
284.6	32.6	979.5	307.4	2826.1	306.4	2963.9	305.4	3032.9	317.4	1999.5
285.0	21.3	980.7	305.4	2826.1	305.1	2963.9	305.4	3032.9	315.4	2068.4
285.6	30.8	996.4	306.4	2826.1	305.3	2963.9	305.4	3032.9	315.4	2068.4
Gainesville to Ft. Lauderdale (315 Miles) -- All Tires Correctly Inflated										
282.7	42.5	994.0	305.4	2688.2	305.9	2826.1	304.9	2826.1	305.9	2826.1
284.1	30.4	995.2	305.3	2826.1	306.2	2963.9	304.4	3032.9	303.4	2895.8
290.0	42.2	995.4	310.3	2826.1	309.2	2963.9	309.4	3032.9	312.4	2895.8
289.3	49.1	1003.7	309.0	2895.0	308.9	3032.9	305.9	3101.8	309.9	2964.7

Proposed Class Implementation

As stated above, this exercise is a sample lesson to illustrate the utility of TDT in an engineering classroom. This method has not yet been implemented in a live class or over an entire curriculum. The impact of TDT on student learning and engagement, therefore, has not yet been evaluated. Given the experimental and hands-on nature of the TDT curriculum, it is envisioned that students will develop and carry out their own test protocol in consultation with course instructors. Depending on the location and facilities of the school implementing TDT, the instrumented car could be driven around a predetermined paved circuit within the campus or at greater speed around one of the many interstate highway beltways surrounding most major U.S. cities. If even greater speed and/or consistency is desired, the instrumented car could be driven between the campus and industrial or government partner facilities when faculty travel for meetings; it could be driven between campus and class fieldtrip destinations; and/or it could be driven to far-flung ASEE regional and national conference locations when students and faculty attend to present research results. If resource limitations, liability concerns, or other factors prevent an instrumented car from being obtained and/or driven for data collection, universities implementing TDT can use the data in Table 1 of this paper to facilitate quantitative analysis.

Implementation Addresses the Three Key TDT Attributes

The first TDT differentiating attribute is a study of the same unifying system of systems in many courses across the curriculum of a degree-granting program. From a curriculum-development perspective, a department-wide commitment and consensus on which system to study are essential. While somewhat unusual, integrated engineering curricula where one unifying system is studied across multiple courses do exist; either organized from the department leadership down [48] or developed organically from the faculty up [49]. Importantly, the selected TDT system need not be an automobile; other paradigmatic systems considered by this research team were 1) cellular phones, 2) drone copters, and 3) buildings. The major requirement in selecting a TDT system is that it is rich, complex, and made up of enough varied sub-systems to warrant detailed study. Certainly, TDT system selection must be governed by a program's curriculum to ensure a logical connection between course topics taught and subsystems evaluated.

This paper's example also demonstrates the full-circle approach taken in TDT, the second unique attribute of this pedagogical approach. Initially, the familiar automobile system of systems {TOP} is introduced. Next, the focus is placed on the tire subsystem which is quantitatively analyzed in detail {DOWN}. Finally, the overall automobile system is revisited to demonstrate how changes to the tire subsystem impact performance {TOP}. While the overall system is set, subsystem selection in each course can be left to instructors, enabling a degree of faculty creativity and flexibility on par with the autonomy granted in non-TDT classes. A tire was selected in this Thermodynamics class example due to ease of monitoring via aftermarket TPMS add-on. However, the car's heating and air conditioning system or its internal combustion engine could have also been the examined subsystem. In a Fluids course the fuel pumping system, engine coolant circulation system, or windshield fluid sprayers might be analyzed. In a machine design class, it might be the crankshaft, the transmission, or the door hinges. The correct overall system selection provides a rich variety of subsystems to study.

TDT provides for more than just a theoretical analysis of the automobile and its subsystems. The third unique TDT attribute illustrated here is a hands-on, project-focused, laboratory-based approach to teaching and learning. In this example, a real automobile and its tire subsystem were instrumented. An experiment was designed and carried out. Resulting data were analyzed to help develop practical understanding that will buttress and complement classroom-taught theory.

Conclusions

A new closed-loop educational paradigm called TOP-DOWN-TOP (TDT) is reported. The educational hypothesis underpinning TDT is that by 1) utilizing as a teaching laboratory a complete, familiar, real-life system [an automobile] that contains many sub-systems {TOP}, 2) identifying subsystems relevant to courses in the curriculum and teaching how those components function via fundamental science and mathematics {DOWN}, and 3) returning to the full scale system to examine how changes to the subsystem impact performance {TOP}; students experience a high level of confidence and excitement for learning arising from inspiration, engagement, motivation, and persistence.

Here, a preliminary example of data collection for a TDT Thermodynamics lesson is described. A 2008 Toyota Highlander SUV was augmented with TPMS to monitor tire pressure and

temperature. The SUV was then driven ~587 highway miles with one underinflated tire and ~315 highway miles with all tires correctly inflated. Tire pressure and temperature data were collected at regular intervals as were ambient outdoor conditions. A Thermodynamic First Law energy balance model was developed showing how the underinflated tire runs at elevated temperature due to excessive mechanical deformation, which increases tire rolling resistance. Increased tire temperature was then correlated to reduced fuel economy with a predicted reduction from 23.29 to 20.34 mpg. This modeled result compares very well with the 20.29 gas mileage actually measured when the SUV ran on one underinflated tire.

The analysis is presented in the context of three unique attributes differentiating TDT from other pedagogical approaches.

1. One selected system of systems unifies all courses in the TDT curriculum by appearing again and again in each TDT class.
2. A closed-loop, multi-scale approach is used to present the selected system to students
3. The teaching approach is hands-on, project-focused, and laboratory-based

Finally, a brief discussion is provided about how an example system of systems should be selected and how TDT might be practically implemented on the scale of an academic engineering department.

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