Incorporating a Design of Experiments (DOE) Project into a Sophomore Level Introduction to Engineering Design Course

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Abstract
The task of teaching the engineering design process at the sophomore level can be enhanced by judicious use of hands-on projects which allow the students to put into practice the concepts and methods being taught. The challenge for the instructor is creating and administering meaningful and pedagogically productive projects that are feasible within the time and resource constraints. This paper describes a project that manages to integrate into one activity, a large number of skills and learning objectives consistent with current ABET criteria. Students plan and execute a simple but meaningful project that starts with the application of the design process to meet specific design requirements. In the design stage students use CAD 3D solids modeling software to model all parts and assemblies, and determine the required mass properties. Once the specifications are met, the student teams generate G code for manufacturing the primary part on a 3-axis computer numerically controlled (CNC) mill. Once the assemblies are manufactured students run performance tests on their "products" using statistical design of experiments (DOE) methodology to evaluate the effects of two factors at two levels (2x2) and determine the setup giving the best performance. The project culminates in a written technical report, which the student teams present orally to an audience of their peers and a panel of faculty and staff evaluators.

Introduction

BAE202 (Intro to BAE Methods) introduces basic design and problem solving methodology for Biological Engineering. The majority of the students are enrolled in the Biomedical Engineering curriculum with the remainder in Biological Engineering, which offers concentration areas in bioprocessing, environmental, and agricultural engineering.

The learning objectives for the course support the requirements of both curricula by emphasizing content and learning experiences that parallel several ABET EC2004 criteria [1]. In particular these include, (3b) an ability to design and conduct experiments, as well as analyze and interpret data; (3c) an ability to design a system, component, or process to meet desired needs; (3g) an ability to communicate effectively; and (3k), an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

The portion of the course emphasizing visualization and graphical communication skills includes computer-aided 3-D solid modeling of parts, 3-D assembly of solid part geometries, computation of mass properties, reading and creating 2-D engineering drawings. Other topics include the engineering design process, safety, tools, and basic fabrication/manufacturing processes and the hands-on design and construction of a metalworking project.

During the semester, students work through textbook exercises to familiarize themselves with solids modeling, assembly, and the creation of engineering drawings using Pro/Engineer®, which is a sophisticated computer aided design (CAD) package. This software permits the designer to create virtual models of parts or assemblies. In part mode, features such as protrusions, cuts, holes, and rounds are added to capture design intent and create all the features necessary to represent the complete part. Individual parts can then be combined in assembly mode by specifying constraints to locate the parts with respect to each other or with respect to established datum features. Created features are parametric and can be modified at any time causing the entire model, parts, drawings, and assemblies, to update and reflect the changes. Program modules for analysis, integrated manufacturing, report generation, and drawings enhance the utility of this software as a comprehensive tool for product design.

Our experience has shown that tutorial-type textbook CAD exercises cannot be relied upon as the sole basis for CAD instruction. A click-by-click set of instructions can lead to an incomplete grasp of important underlying concepts and a lack of ability and confidence when faced with less well-defined problems. To supplement and reinforce the learning experience, special projects are assigned. These projects are more open ended in nature and require the students to think, make decisions on approach and methods, and integrate and homologate information from various sources.

This paper describes a multi-faceted student project initiated in Spring 2002 that is directed at all the learning outcomes listed above. The assignment is given in the final three weeks of the semester and serves as a means to reiterate the CAD and design process skills learned, and to allow the introduction of the DOE topic. Students are assigned to teams of two, and each team does all the work necessary to complete a project.

Project Background and Description

The Pinewood Derby (PWD) is an annual highlight of many Cub Scout packs across the nation. Cub Scouts and their fathers strive to fashion a winning car out of a standard derby car kit, which consists of a wooden block, plastic wheels, and steel axles. Cars are prepared according to a set of specifications that establishes wheel locations and a maximum weight allowance of 5 ounces. Scouts compete by racing their cars down an inclined track. Basic human nature inevitably leads to heated competition tempered by fun and good sportsmanship.

Theories abound as to which characteristics of the cars exert the greatest influence on speed. Minimizing friction is obviously an important consideration. Scouts (or their fathers) often spend hours buffing wheels and polishing axles to remove any burrs or imperfections that might reduce speed on the track. Aerodynamics is commonly thought to be important. However, reductions in the coefficient of drag are generally not very significant at these low speeds. Another commonly held belief is that car speed is dependent on mass. The idea is that adding mass to a car increases its momentum and, therefore, decreases the net effect of forces opposing the motion of the car. However, more weight also leads to more friction in the wheels and increased rolling resistance that dissipates energy and decreases speed. Thus, it seems that there should be some optimum level of mass, which will maximize speed and minimize run time on the track. Additionally, and perhaps more importantly, the placement of ballast weights on a car affects its mass distribution. Adding mass to the rear moves the center of gravity to a higher elevation as it sits in the starting position on the inclined track. This increases the car's potential energy. The tradeoff here is that instability on the track can cause a significant reduction in speed. Shifting the auxiliary mass to the rear tends to reduce the mass moments of inertia with respect to a rear axle origin that may decrease stability and compromise speed.

This engineering conundrum was the genesis of this project. The main objective of the project was to challenge a class of budding young engineers to approach this familiar problem (many of the boys had already wrestled with these questions as youngsters racing the PWD cars but the girls in the class showed just as much interest and enthusiasm) using the methods and approaches a real world engineer would use to try and answer some of these basic design issues. Specifically, we wanted to exercise modern engineering tools for design and manufacturing and conduct a designed experiment to reach conclusions about the influence of the amount of mass and the mass location upon PWD car performance.

BAE202 students were asked to design, construct, and test a gravity propelled model racecar with basic specifications similar to those stipulated by the Boy Scouts of America in their annual Pinewood Derby competition. [2] Students were required to:

a) develop a design package by first creating 3D solid CAD models of the car body, the wheels and axles, and the auxiliary masses to be added as ballast,
b) perform appropriate analyses using Pro/Engineer® to compute volumes, weights, mass properties, etc.
c) use a 3-axis computer numerical control (CNC) mill to manufacture the car body and then assemble their car using standard Pinewood Derby wheel kits and auxiliary masses provided,
d) test the performance using design of experiments methodology to determine the effects of mass and mass location on performance,
e) analyze the data and reach conclusions about the test results,
f) write a project report in technical paper format, and
g) present their team's project report orally to the class making use of visual aids.

Students had to reverse engineer the wheels and axles for use in the Pro/Engineer® assemblies since wheel and axle kits were purchased and provided to each team.

The Design Requirements

Students were asked to design a car that conforms to the basic constraints shown in Figures 1 and 2. A rigid polyurethane foam material (Sign-Foam ™, General Plastics Mfg. Co., Tacoma, WA) was used for the car bodies rather than the standard Pinewood Derby kit pine block. Machining properties of this lightweight material facilitated the manufacturing process. The small mass of the car body allowed a larger percentage of the 5 ounce total to be auxiliary masses, making possible, significant changes in mass properties as a function of the location of these weights for the different configurations used in the designed experiment tests. Cutouts were specified at the front and rear of the car body for placement of the auxiliary weights. These cutouts are as shown in Figure 1.

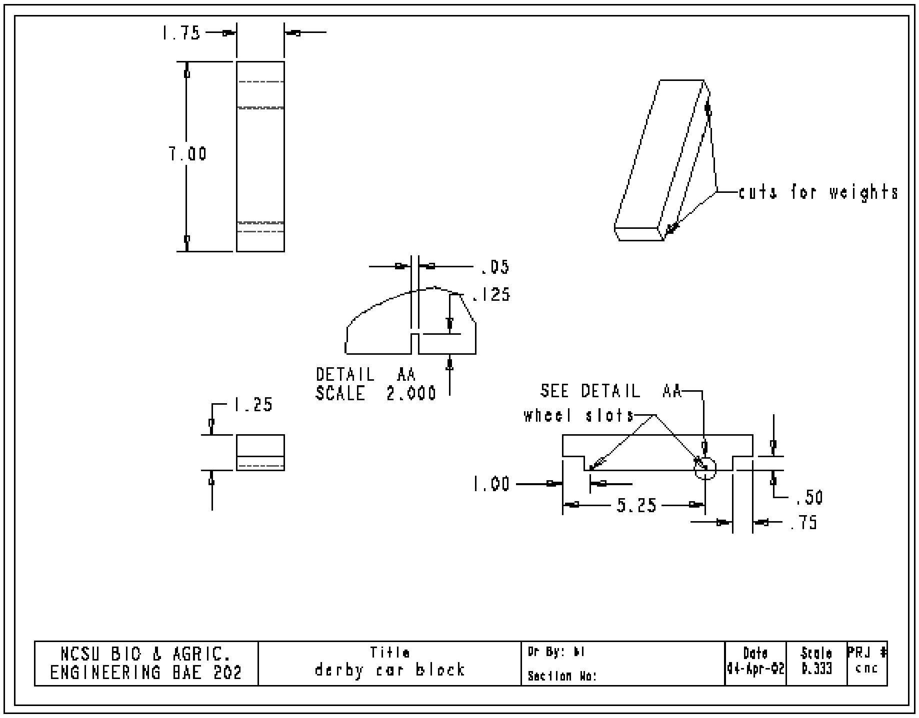


Figure 1. Specification of the maximum geometric envelope defining the required width at the axle mounting regions and the length and height of the raw block from which the car bodies were to be designed and made. Wheel (axle) mounting slots, and notches for the auxiliary weights, were required to be the same for each team as controlled variables for the tests.

Specifications for the derby car are as follows.

1. Basic dimensions for the block are 1.25"x1.75"x7.00".
2. Slots for the wheels should be 0.05"x0.125".
3. Position of wheel slots are indicated on the drawing.
4. Cuts for weights should be as indicated on the drawing.
5. Position of the cuts for weights are indicated on the drawing.
6. Weight dimensions are 0.25"x0.75"x1.75".
7. 2 weights will be utilized.
8. Total weight of finished car should be 5.0 oz.
9. Block material is rigid foam (density of 0.133 oz/in^3).
10. Weight material is steel (density is 4.512 oz/in^3).
11. Wheel and axle mass is 4.35g.
12. 4 wheels and axles per car.

Design car body such that finished assembly meets the specifications as described. Include the slots for the wheels and the cuts for the weights in your design.

Figure 2. Specifications in addition to the drawing in Figure 1 given to the teams as constraints for their derby car designs.

Pro/Engineer® calculates mass properties and performs analyses according to a selected set of units for length, mass, and time. The default set is inches, pounds-mass, and seconds. This set can be changed at any time according to the desire of the user. However, the designer must be aware of the current setting to insure the accuracy of the model. Material density information was provided in a variety of units. Some values were given in English units while others were expressed in metric units. The total mass was given for the wheels and axles together. The axles were known to be steel but the exact wheel material was not known. Students were required to measure the actual wheel geometry, construct the CAD solid model of the wheel, and perform an analysis to calculate the volume and compute density. The densities of the other materials were given.

Using the masses of the axles, wheels, auxiliary ballasts, and the density of the foam body, the students determined the maximum car body volume permitted in order for the completed assembly to have a weight of 5 ±0.1 ounces. Once the car body CAD models were created, the students were required to complete the assembly of their cars in Pro/Engineer® in accordance with five different auxiliary weight configurations to be used in the controlled experiment tests. For each of these assemblies the students were required to compute the mass properties with the coordinate system placed at the right rear axle with the y-z plane in the right side plane of the car. The five setups for the CAD and actual physical assembly models are summarized in Figure 3. The (*,*) designations indicate the (mass factor, location factor) levels for each setup. The "+" level of mass indicates two weights (both masses), while the "-" level is one auxiliary mass. The "+" location factor was chosen to correspond to the rear location and the "-" level of location was assigned the front. The mid level setup used two special weights each weighing 75% of a single standardized-run weight so that the combined auxiliary mass for that mid level setup was midway between the "–" and "+" levels, i.e., 2.25 ounces. The equivalent of mid level location was approximated by placing one of these weights in the front and one in the rear. Figures 4 and 5 show samples of some CAD assembly models generated by students.

1. 2 weights (3 oz.) in front (+,-)
2. 2 weights (3 oz.) in rear (+,+)
3. 1 weight (1.5 oz.) in front (-,-)
4. 1 weight (1.5 oz.) in rear (-,+)
5. mid-level setup: 1 weight front and 1 weight rear with each weight = 1.125 oz. so total weight is midway between 1.5 oz. and 3.0 oz. or 2.25 oz.

Figure 3. The five car assemblies required in anticipation of a 2 factor, 2 level (2x2) designed experiment where one auxiliary mass weighted 1.5 oz so the two weights made up 3 of the 5 oz total weight of the cars.

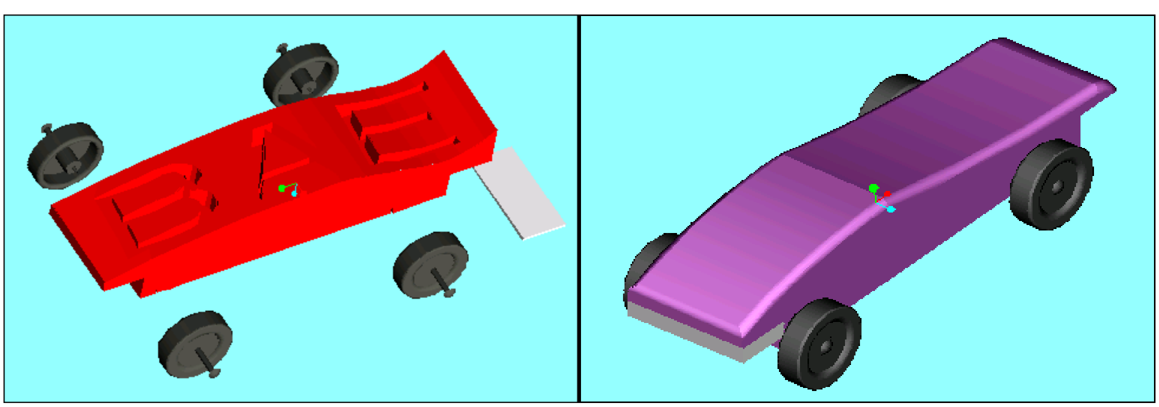


Figure 4. Exploded CAD assembly model. Figure 5. CAD model showing (+,-) setup.

Manufacturing the Cars

Car bodies were fabricated on a 3-axis MAXNC® desktop CNC milling machine (Figure 6). The G code program for driving the mill was generated by the students using the Pro/Manufacturing module of Pro/Engineer®. They were able to do this after working through a tutorial that was delivered to them in PDF format in the secure class locker web space. The required machining parameters such as tool dimensions, cutting speeds, mill path patterns, surface offsets, and cut depth were provided to the students by posting the data in the same locker space. Once all of the required parameters were set, Pro/ENGINEER® determined the material to remove from the work piece and calculated the tool path trajectories. The machining operation could be simulated on the computer screen to provide a visual check for errors. If the results were deemed satisfactory, the G code was generated and saved into a designated file directory for access by the CNC milling operation that followed.

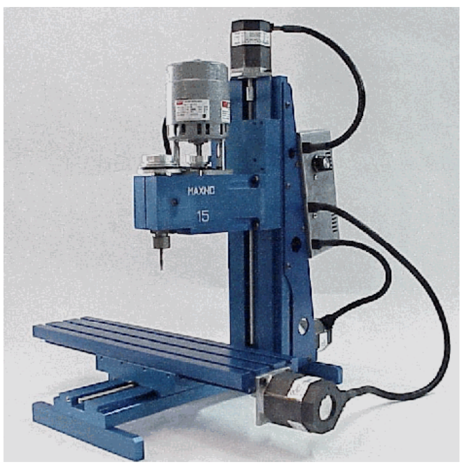


Figure 6. The 3-axis MAXNC® mill used to manufacture car bodies. This operation was done with minimal student participation outside class time. It was not deemed feasible to expect each team to use this equipment independently with the short time available for training.

Preparing Students for the Testing Phase by Introducing the DOE Topic

The "design of experiments" topic is normally found in graduate level statistics courses, but DOE methodology as an engineering tool can be introduced effectively at the undergraduate or even secondary school levels.[3] The experimental setup and the data collection and analysis techniques required in this project were introduced by demonstrating and discussing a similar experiment. The methods illustrated in the demonstration served as a model that the students were able to extrapolate to the derby car project. The selected model was patterned after the well known "funnel experiment" discussed in the literature.[4,5,6] Other helpful introductory resources on design of experiments are available.[7]

The funnel experiment apparatus consists of a tube that serves as a chute for the introduction of a steel ball bearing into the top of a funnel. The response variable is the dwell time of the bearing in the funnel, and the objective is to determine the factor settings that maximize this time. Materials used in this demonstration consisted of an 18" long, 0.5" ID, straight copper tube serving as the conduit for a 0.336" diameter steel bearing. The funnel was plastic with a top diameter of 7.7" converging to 1.25" at a depth of 5" then to an outlet diameter of 0.5" at a final total depth of 7.5".

The funnel was mounted in a fixed upright position on a wooden stand. The exit end of the copper tube was pivotally located about 1" above the upper edge of the funnel and directly above the top rim. Two protractor scales were used to measure the orientation of the tube. One protractor measured the horizontal angle, with 0° placing the tube tangential to the funnel circumference, whereas at the 90° direction, the chute direction intersected the axis of the funnel. We called this factor the angle, "A". The other angle was the slope of the tube measured in a vertical plane, which we called height, "H". Zero degrees for this factor corresponded to a horizontal tube position.

The dwell time is a function of the speed and trajectory of the ball bearing as it circum-navigates the conical surface. This was measured using a manually operated electronic stopwatch capable of reading to the nearest 0.01 seconds. The stopwatch was started when the bearing was seen exiting the end of the tube (entering the top of the funnel) and stopped when it dropped into a cup placed under the funnel to recover the bearing after each run.

These materials were brought into the classroom and the details of the setup were explained to the class in preparation for actually running the live experiment during the class period. The students were asked think about this DOE demonstration as a model for their setup of the Pinewood Derby test project. The funnel experiment was run as a two level, two factor (2x2) design. Preliminary test runs were conducted to select the operating ranges for each factor. The maximum and minimum heights of the tube corresponded to the coded "+" and "-" levels respectively of factor H. These coded levels mapped to approximately 12° and 5° degrees in uncoded, or actual, physical dimensions. Larger height angles resulted in the bearing jumping out the top of the funnel at some angle positions. Similarly the angle factor, A, was chosen at 35° for the coded "–" level and 70° for the "+" level. This gave a test matrix as follows involving 4 test setups where (*,*) are coded (angle, height) levels respectively:

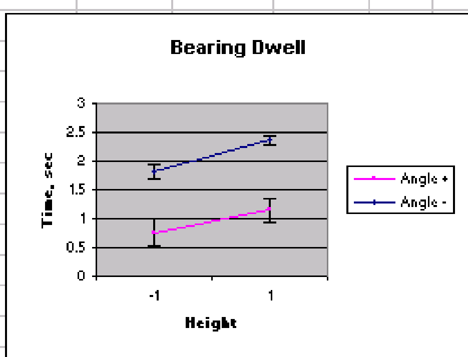
$$\text{Height}\begin{bmatrix} (-,+) & (+,+) \\ (-,-) & (+,-) \end{bmatrix}$$
$$\text{Angle}$$

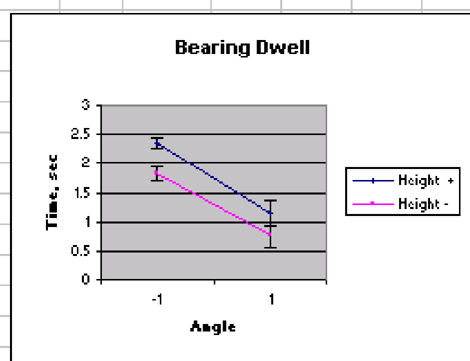
Standardized Run number	Randomized run # (example)	Angle A	Height H	Interaction AH	Average Of Reps
1	3	-	-	+	R_{A1}
2	1	+	-	-	R_{A2}
3	4	-	+	-	R_{A3}
4	2	+	+	+	R_{A4}
Effect		A effect	H effect	AH effect	

Where the "A effect" = $(-R_{A1} + R_{A2} - R_{A3} + R_{A4})/2$
The effect for "H effect"= $(-R_{A1} - R_{A2} + R_{A3} + R_{A4})/2$
The interaction "AH effect"= $(R_{A1} - R_{A2} - R_{A3} + R_{A4})/2$
Where R_{Ai} are the averages (Ravg) of four reps (Ri) for each of the standardized runs 1 through 4.

Figure 7. The basic test planning matrix for the funnel experiment.

	factor A	factor H	AH	R1	R2	R3	R4	Ravg	s^2	SE	t*SE	Ravg +	Ravg -
	-	-	+	1.87	1.88	1.69	1.82	1.815	0.006	0.040	0.127	1.942	1.688
	+	-	-	1	0.56	0.63	0.87	0.765	0.019	0.069	0.220	0.985	0.545
	-	+	-	2.47	2.34	2.38	2.25	2.36	0.003	0.029	0.091	2.451	2.269
	+	+	+	1.09	1.12	1.34	1.03	1.145	0.017	0.065	0.208	1.353	0.937
effects	-1.1325	0.4625	-0.0825										
midpoint runs				1.59	1.25	1.47	1.5	1.4525					





time= midpt avg + (effect A)/2*A +(effect H)/2*H+(effect AH)/2 *A*H
Thus time=1.45-1.13/2 * A +.46/2 *H - .08/2 * A* H

Figure 8. The spreadsheet showing a sample of the funnel experiment data and analysis used in the introductory DOE demonstration for the class. A handout discussing this experiment and the analysis of the data was posted in PDF format in a web based course locker for the students to access and study.

In addition, a mid-point test setup was also included. This was a height level, H, midway between 5 and 12° or 8.5° and an angle, A, of (70+35)/2 or 52.5°. Four replications were run as a live demo in class for each of these five setups. The data was entered by students into a test matrix on the white board for the class to see.

Run order was randomized for each test setup using a random number table. Four replications were run in succession without changing the setup. In table form, the test matrix looked as shown in Figure 7 below. A sample spreadsheet of the funnel experiment results and analysis is shown in Figure 8.

The variance for each test setup was computed as:

$$s^2 = \sum_{i=1}^{4}((Ri - Ravg)^2)/(n-1)$$

Where the (Ri-Ravg) are the differences of individual reps from the average of that set of reps and n=4, the number of tests.

Assuming normality, confidence intervals for each mean (Ravg) were computed by estimating the standard error (SE) of the means and then using the students t distribution for 95% confidence levels.

$$SE = \sqrt{s^2 / n}$$

With four samples (runs), we had three degrees of freedom for the standard deviation in the "t" table which at 95% confidence gives a "t" value of 3.18. The confidence interval was computed as $\pm$(t)*(SE) for each test mean. Hence the confidence interval on each setup's average was $\pm$(3.18)*(SE), shown as Ravg+ and Ravg- in Figure 7. These ranges are shown as error bars on the effects charts. Lack of overlap indicated a significant difference at a 95% confidence level for both effects. Stated another way, the effect of height was significant at all angle settings. Likewise the effect of angle on dwell was significant at all heights within the coded range tested. The essentially parallel effect plot lines indicates a lack of strong interaction between the two effects. The longest dwell time is obtained with the angle is set at its low value (entry tangential to the funnel circumference) and with a high value of height, H +, which gives high velocity to the bearing. This result coincides with what we would expect, since a bearing entering tangentially at the top of a funnel with high kinetic energy will circumnavigate the funnel many times before dropping out the bottom. This conclusion is true only within the ranges of A and H that allow the system to perform in a stable manner. It is important to emphasize with the students that the coded ranges of the effects parameters much be within tolerable operating limits for the system.

Running the Designed Experiment on the PWD Cars

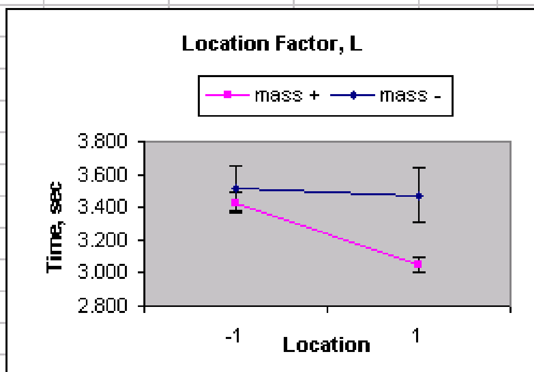
The student's objective in running a two factor, two level (2x2), test was to determine the effects of total mass and mass distribution (location) on performance of the Pinewood Derby car. The influence of other factors was mitigated through the design of the experiment. Each team's car obviously had some design and quality or tolerance parameters that affected the results differently than other cars. These variations were blocked by having each team's test results analyzed individually. Each team reached its conclusions about the mass and location effects solely on the basis of their car's design and performance results. This allowed all factors except mass and mass location to be controlled run to run. Cars were not competing against each other. The tests were run on a standard 28 ft long pinewood derby track obtained from a local Scout troop. The track allowed two cars to be run simultaneously.

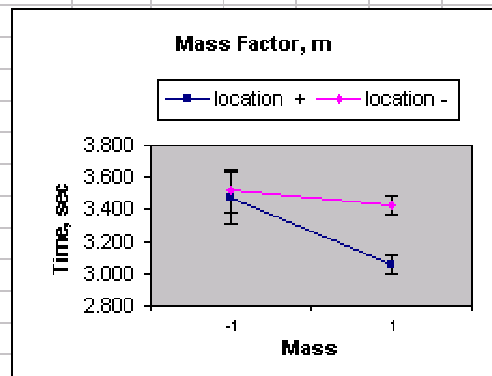
Cars were timed electronically with the aid of a data acquisition card (DAQCard 1200) from National Instruments and a simple LabVIEW™ program VI (virtual instrument). The car release mechanism was equipped with a micro switch to signal the start of the run. The finish gate at the end of the track was equipped with vertical LED light beams and phototransistors that were triggered as the cars crossed the finish line. The elapsed time between the start and finish signals was displayed to the nearest thousandth of a second on a large LabVIEW® indicator on the PC display. Teams assigned one member the task of retrieving the car, assuring proper setup for the test run, and placing the car on the track. The other team member recorded the run times in the proper location on their test matrix spreadsheet. Each car setup listed in Figure 3 was tested four times in randomized run order.

Each team was required to write a comprehensive project report covering all aspects of the project in technical paper format. This included the details of the design process, tables showing the mass properties of each of the five test setups obtained from the CAD assembly models, the analysis of the test data and a discussion of the results and conclusions. These reports were handed in after the team made an oral (10 minute) presentation to the class. Oral presentations were judged by faculty and staff using a rubric provided to the students in advance. Peer evaluations were tried in some sections but these generally resulted in perfect scores for every team so this evaluation method was discontinued.

As a point of interest, most teams found that the best performing car setup was the (+,+) combination that placed the maximum auxiliary mass (3 ounces, both weights) at the rear of the car. A few teams found the best time was for the (+,-) setup but were able to explain the result on the basis of observed unstable behavior of the car on the track caused their car body mass distribution combined with the rear location of both auxiliary masses. On some cars, the front wheels carried essentially no weight, which resulted in wobble down the track.

	factor m	factor L	mL	R1	R2	R3	R4	Ravg	s^2	SE	t*SE	Ravg +	Ravg -
	-	-	+	3.397	3.531	3.471	3.667	3.517	0.007	0.042	0.134	3.651	3.382
	+	-	-	3.503	3.416	3.354	3.44	3.428	0.001	0.019	0.061	3.489	3.367
	-	+	-	3.388	3.426	3.441	3.649	3.476	0.011	0.051	0.164	3.640	3.312
	+	+	+	3.116	2.997	3.052	3.049	3.054	0.001	0.014	0.043	3.097	3.010
effects	-0.255	-0.208	-0.167										
midpoint runs				3.156	3.339	3.468	3.467	3.36					





time= midpt avg +(m effect)/2 *m + (L effect)/2 *L + (mL effect)/2 * m*L

Thus time=3.36-0.255/2 * m -0.208/2 *L - 0.167/2 * m* L

Figure 9. Sample spreadsheet showing the PWD car test data from one team.

The test data in Figure 9 shows that for this car there was a strong interaction between the mass factor, m, and the location factor, L as noted by the non-parallel effects plot lines. The plots also show that at the front location the amount of ballast does not make at significant difference in performance at the 95% confidence level as shown by the overlapping error bars. Also the plots show that at a low level of mass, the mass location factor, L, does not significantly affect performance. However when a high level of mass is used ,m+, there is a significant location effect with the fastest track time occurring at L+ or rear location and at that location m+ is significantly better than m-. The predictive time equation is valid only for the coded values of the effects, i.e., m at +1 or –1 and location, L at + 1 or – 1 in the equation. Using the coded values in this way allows the coefficients to be interpreted. For example the equation shows that the interactions coefficient is large compared to the mass and mass location coefficients which is what the plots imply.

Summary

This project brought together many aspects of engineering design that we wanted to emphasize in this course. Students were required to design and create parts and to combine the parts into assemblies using powerful modern CAD/CAM engineering tools. They analyzed the assemblies to determine mass properties. They were introduced to CNC manufacturing operations and G code generation and how G code can be used to control stepper motors (on the 3-axis mill). They conducted a designed experiment and performed a statistical analysis to determine the effects of two selected design parameters and whether the factors were significant at the 95% level of confidence. They prepared a report including their design package, test results and conclusions, and the presented these reports before an audience of their peers and a panel of faculty and staff evaluators.

Students received the assignment with great interest and enthusiasm. Some felt it was a lot of work. It certainly was ---especially for the instructor and one teaching assistant handling four sections of students (65 total). The most time-consuming task was the milling of each car from the submitted G code files. The small 3-axis mill was rather slow even on the rigid foam material. In preparation for next semester, a 3-axis ShopBot® CNC router has been purchased which will be able to mill the car bodies much more rapidly. Otherwise, we plan to run the project next time essentially in the same fashion as described. This project has more engineering, manufacturing, and statistical content than some of the projects used formerly. A few students said they would have liked more “shop” time, but the evaluations were generally very positive. Overall, we feel this project module links together many concepts and hands-on learning experiences that will prove to be of lasting value to our students.

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Biography

Larry F. Stikeleather has been professor of Biological & Agricultural Engineering at North Carolina State University since 1985. He earned his Ph.D. degree in Biological & Agricultural Engineering in 1968 and worked 18 years in industrial research and management. His research interests include biomechanics, vibration effects and controls, human factors, rapid extraction of bioactive compounds, and mechanization.

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