Title
Shigley Hauler— A competitive project illustrating basic machine design principles

Journal
International Journal of Mechanical Engineering Education, 44(4)

ISSN
0306-4190

Authors
Farouki, Rida T
Linke, Barbara S

Publication Date
2016-10-01

DOI
10.1177/0306419016669189

Peer reviewed

Shigley Hauler — a competitive project illustrating basic machine design principles

Rida T. Farouki and Barbara S. Linke
Department of Mechanical and Aerospace Engineering,
University of California, Davis, CA 95616, USA.

Abstract

By requiring students to meet demanding functional specifications using limited resources, the competitive *Shigley Hauler* project offers undergraduate students practical "hands–on" experience in the design, fabrication, and testing of mechanical systems. The project imparts a thorough experiential understanding of the key principles that govern the selection and integration of basic machinery components — gears, shafts, bearings, DC motors, etc. — into a robust and efficient working system. The *Shigley Hauler* project has been successfully incorporated into the mechanical engineering curriculum at UC Davis for more than a decade, and its pedagogical and motivational value is corroborated by student feedback. The project is run within a 10–week timeframe, and entails only modest costs for the instructor and student teams.

Keywords: Mechanical design; machine components; design competition.

e–mail addresses: farouki@ucdavis.edu, bslinke@ucdavis.edu

1 Introduction

A thorough grasp of the basic principles underlying the design, selection, and integration of mechanical components into a working system, that efficiently and reliably satisfies a prescribed function, is a key element of the mechanical engineering curriculum. At UC Davis this requirement is addressed through two quarter–long Mechanical Design courses, EME 150A & B, based on the classic textbook *Shigley's Mechanical Engineering Design* [1].

Students typically take EME 150A & B in their junior or senior year as a lead–in to their capstone design class, in which they address "real–world" engineering design projects proposed by sponsors from academia or industry. The emphasis in EME 150A is on analyzing stress in mechanical components, and ensuring safe operation under specified static or cyclic loading conditions. In EME 150B the focus is on understanding the properties and functions of basic machine components (gears, bearings, cams, shafts, couplings, springs, fasteners, etc.) and their selection and integration in order to guarantee the desired machine performance, reliability, safety, and longevity.

Experience shows that "hands–on" projects (and especially projects of a competitive nature) play a key role [2, 4, 5, 6, 7] in eliciting and sustaining the enthusiasm of students for material that may seem rather dull if restricted to a lecture–homework–exam delivery style. However, a number of constraints can make the formulation of such projects a non–trivial task — specifically,

- the project task must be amenable to timely completion;
- the analysis should be based on tractable engineering principles;
- the materials and equipment costs should be relatively modest;
- the students must possess the required machine shop training;
- the task should entail teamwork & project management principles;
- success must be demonstrated by implementation and testing.

Guided by these considerations, the *Shigley Hauler* project was developed at UC Davis ~ 15 years ago, and has since been incorporated into EME 150B, resulting in significantly increased enrollments and improved levels of student enthusiasm (as reflected in the course evaluations). The guiding philosophy of the project is to pose a simple but challenging and competitive functional requirement, based on limited power and power transmission resources.

The EME 150B students work on the *Shigley Hauler* in teams of four or five, and are responsible for project time management and division of labor among its various aspects (design, analysis, fabrication, testing, competition participation, report writing, etc.). This helps students develop the teamwork and communication skills that are key aspects of the Accreditation Board for Engineering and Technology (ABET) program review process.

To encourage active participation, the students are informed early in the term that they will conduct peer evaluations [3] of their team members upon conclusion of the project, and systematic evidence of inadequate engagement will result in an individual project grade penalty. Weekly discussion sessions allow the student teams to consult the instructor and the teaching assistants on all aspects of the project. To emphasize its importance, the *Shigley Hauler* project accounts for one–third of the overall EME 150B course grade.

2 Project specification

The goal of the project is to design, analyze, fabricate, and demonstrate a device that is capable of hauling heavy weights along an inclined plane using limited resources. The unit of weight is the *shigley* — i.e., the weight[1] of the (hardcover edition) of the *Shigley's Mechanical Engineering Design* textbook. The value of this unit is determined empirically, as shown in Figure 1.

The power source used to accomplish this task is a Mabuchi RE–280RA permanent–magnet DC motor [8] running off two 1.5V AA alkaline batteries. This motor is available, at modest cost, from a number of sources. Operating at 3V, it has (see Figure 2) the linear torque–speed characteristic

$$T \,=\, T_s \left(1 - \frac{n}{n_0}\right) , \tag{1}$$

where T is the motor torque in Nm and n is the motor speed in rpm. The motor operation is completely characterized by two simple parameters — the *stall torque* $T_s = 0.0127$ Nm, and the *no–load speed* $n_0 = 9200$ rpm.

The *maximum* power output is achieved when the motor operates at the mid–point of the characteristic ($T = \frac{1}{2}\,T_s$ and $n = \frac{1}{2}\,n_0$), and corresponds to the modest value of approximately 3.06 W. Complete technical specifications

[1] Students who are accustomed to lugging this tome around campus in their backpacks can attest that it is indeed a very substantial unit of weight.

Figure 1: Empirical determination of the *shigley* load unit.

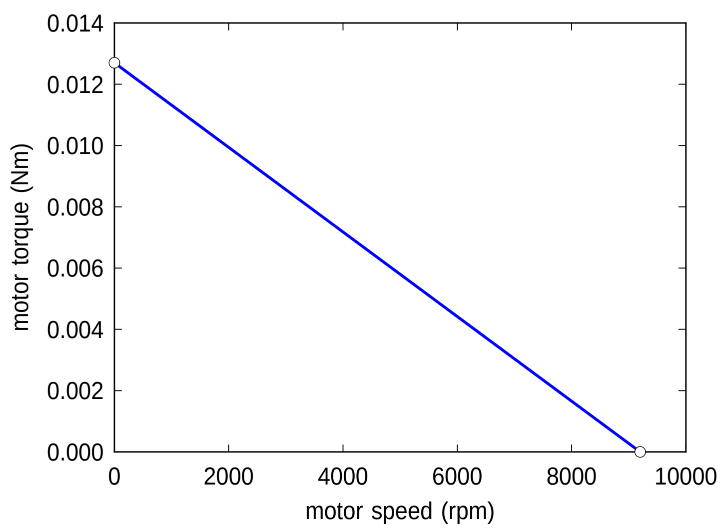

Figure 2: The torque–speed relation (1) for the Mabuchi motor operating at 3V, with the no–load speed $n_0 = 9200$ rpm and stall torque $T_s = 0.0127$ Nm.

for this motor, including efficiency and current draw, may be found on the webpage [8]. The simple DC motor characteristic (1) eliminates the need for a sophisticated controller, and facilitates the *Shigley Hauler* analysis — see Section 4 below — based on elementary principles of mechanics.

In addition to the motor, each student team receives a set of plastic spur gears — two in each of the 10, 20, 30, 40, and 50 tooth sizes. The gears come with inserts that are suitable for mounting with an inteference fit on a $\frac{5}{64}$ inch diameter shaft, or can be used without the inserts on $\frac{5}{32}$ inch diameter shafts (with the insert, the 10 tooth pinion mounts with an inteference fit directly on the motor shaft). The gears are available from Jameco Electronics [9], and are of modest quality. These are the only gears allowed for the project: no substitutions may be made. Also, no power source (springs, falling weights, etc.) other than the DC motor running off 2 AA batteries is allowed.

Figure 3: The Mabuchi RE–280RA permanent magnet DC motor and plastic spur gear sets (two each of 10, 20, 30, 40, and 50 tooth sizes) with inserts.

The competition ramp is shown in Figure 4. The lanes are 1 ft (0.305 m) wide, to accommodate the load of *shigleys* in landscape orientation, and 3 ft (0.914 m) long. The load must begin behind a starting line 8 in (0.203 m) from the bottom edge. The top of the ramp incorporates a barrier (not shown in Figure 4) to which the *Shigley Hauler* may be secured with C clamps.

Other than those outlined above, no *a priori* constraints are placed on the *Shigley Hauler* design. Occasionally, some teams may exhibit Rube Goldberg

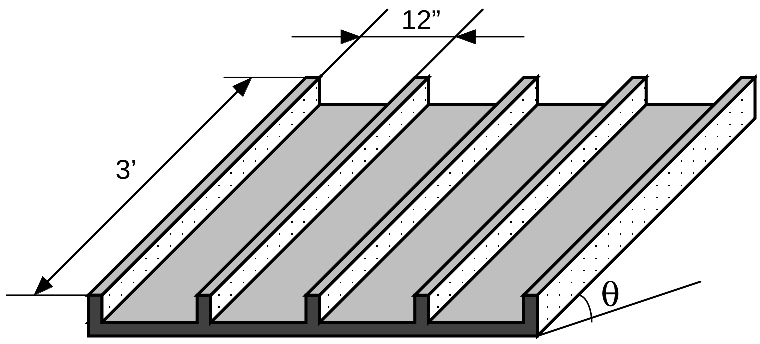

Figure 4: Schematic of test ramp for the *Shigley Hauler* competition.

inclinations. Although the final design is the prerogative of the student team, it is emphasized that a clear focus on the functional specification, leading to a simple device based on meticulous analysis, precision implementation, and thorough testing and troubleshooting, is most likely to be successful.

3 Design, fabrication, and testing

The first task is to complete a thorough design and performance analysis of the *Shigley Hauler*. This task encompasses the gear train layout and resulting reduction ratios, design of the gear shafts (including shaft deflection analysis) and their mounting on appropriate bushings or bearings, the methodology for hauling the load up the inclined plane (typically by wrapping a line around a spool driven by the gear train), and analysis of the expected timings for runs corresponding to different loads and ramp inclinations. Continuous guidance on the design is provided by the instructor and teaching assistants, but the final design decisions are the responsibility of the student teams. Once the design has been finalized, fabrication of the *Shigley Hauler* can begin.

At UC Davis, the EME 50 Manufacturing Processes class is a prerequisite for EME 150A & B. EME 50 offers a broad survey of various manufacturing technologies through its lecture component, and hands–on training with the lathe, milling machine, drill press, etc. — both manual and CNC — in the UC Davis Engineering Fabrication Laboratory (EFL). Thus, EME 150B student teams already have the equipment and safety training necessary to fabricate their *Shigley Hauler* devices in the EFL. Recent upgrades to the EFL provide the students with access to modern fabrication technologies, including laser and water–jet cutters, a 3D printer, and a 5–axis CNC mill.

The DC motor and gear sets are the only items supplied to the students — they are expected to furnish all other materials and components necessary to fabricating their device. A variety of material choices are typically evident in the fabricated *Shigley Haulers*, including aluminum, steel, plexiglass, wood, and 3D–printed plastics. The use of recycled material is encouraged whenever it does not compromise device performance. The teams are advised to adopt a minimalistic approach to design and fabrication of the cart that holds the load of *shigleys*, to minimize the time and costs invested in it, and to avoid significantly adding to the load. The additional materials/components costs incurred by the student teams are relatively modest — ranging from as little as \$10 for particularly frugal teams, up to a maximum of about \$100.

The student teams are encouraged to complete fabrication at least 2–3 weeks before the competition, to allow adequate time for trouble–shooting, fine–tuning, and testing of the device. Common fabrication problems include improper spacing/alignment of gear shafts, insufficient rigidity of the shafts, insecure or misaligned mounting of gears on the shafts, friction due to poor bearing or bushing shaft supports, etc. As emphasized throughout the term, such problems can be remedied if the fabrication schedule allows sufficient time for this trouble–shooting phase of the project.

4 Dynamic analysis

The *Shigley Hauler* is a competitive project, the goal being to complete each run (corresponding to a specified load and ramp angle) in the least possible time. The choice of key design parameters, such as the gear reduction ratio N and spool radius r, must be tailored to each run by a quantitative analysis, based on the following design variables and physical quantities.[2]

- $T_s = 0.0127$ Nm, motor stall torque
- $\omega_0 = 963.4$ rad/s, motor no–load speed
- $g = 9.81$ m/s^2, gravitational acceleration

[2]Henceforth, angular speeds will be expressed in units of rad/s rather than rpm.

- N = gearbox reduction ratio (dimensionless)
- ω = motor angular speed (rad/s)
- T = motor torque (Nm)
- L = total ramp length (m)
- θ = ramp inclination (rad)
- m = mass of load (kg)
- r = line spool radius (m)
- F = line tension force (N)
- v = load speed along ramp (m/s)
- s = distance travelled on ramp (m)

4.1 Steady–state analysis

For a preliminary analysis, the students are advised to ignore transients and estimate run times based on steady–state behavior. When switched on, the motor speed increases from zero and its torque decreases from T_s to a value T just sufficient to move the load at constant speed. The torque NT at the output of the gear box is then equal to the torque rF required to wind a line carrying a tension F around a spool of radius r. In the steady state, the line tension is equal to the component $mg\sin\theta$ of the load weight parallel to the ramp. Hence, the steady–state motor torque is

$$T = \frac{rmg\sin\theta}{N},$$

and from (1) the corresponding steady–state motor speed is

$$\omega_\infty = \omega_0\left(1 - \frac{rmg\sin\theta}{NT_s}\right).$$

Note that this depends only on the *ratio*

$$\rho := \frac{r}{N} \tag{2}$$

of the spool radius r and gear ratio N, and not individually on these design parameters. In order for ω_∞ to be positive, we must have

$$\rho \,<\, \frac{T_s}{mg\sin\theta} \,=:\, \rho_{\max}\,. \tag{3}$$

For a given load m and ramp angle θ, this condition indicates the (theoretical) maximum value of the quantity (2) that does not stall the *Shigley Hauler*. The condition (3) is equivalent to stating that the product of the spool radius r and line tension $F = mg\sin\theta$ should not exceed the motor stall torque T_s amplified by the gear ratio N at the output of the gearbox.

Since the steady–state gearbox output angular speed is ω_∞/N, the linear speed of the load along the ramp is $v = \omega_\infty r/N$. Thus, if the ramp is of total length L, the estimated run time $\Delta t = L/v$ (based on steady–state analysis) can be expressed in terms of the quantity (2) as

$$\Delta t \,=\, \frac{LT_s}{\omega_0\rho(T_s - mg\sin\theta\,\rho)}\,. \tag{4}$$

The value of ρ that achieves the (theoretical) minimum run time is identified by setting the derivative of Δt with respect to ρ equal to zero. This gives

$$\rho \,=\, \frac{\frac{1}{2}T_s}{mg\sin\theta} \,=\, \tfrac{1}{2}\rho_{\max}\,, \tag{5}$$

which corresponds to the case where the motor operates at the mid–point of the characteristic (1), i.e., the maximum power point, and the corresponding (theoretical) minimum run time, under the steady–state assumption, is then

$$\Delta t_{\min} \,=\, \frac{4Lmg\sin\theta}{\omega_0 T_s}\,. \tag{6}$$

4.2 Transient analysis

Since the motor does not achieve the steady–state speed instantaneously, the expressions (4) and (6) are necessarily optimistic estimates of the actual and optimum run times. The system transient behavior can be characterized by a first–order differential equation, whose solution determines a (theoretically) exact run time. Although the students are not required to use this solution, comparing the time constant for this first–order equation with the run time estimate (4) can furnish an idea of how accurate the latter is.

The equation of motion of the load along the ramp is

$$m\frac{\mathrm{d}v}{\mathrm{d}t} \;=\; F - mg\sin\theta\,.$$

Invoking the parameter (2) and the fundamental relations

$$T \;=\; T_s\left(1-\frac{\omega}{\omega_0}\right), \quad rF \;=\; NT\,, \quad v \;=\; \frac{\omega r}{N} \;=\; \frac{\mathrm{d}s}{\mathrm{d}t}\,, \tag{7}$$

it can be cast as the first–order differential equation

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} \;=\; \frac{T_s}{m\rho^2} - \frac{g\sin\theta}{\rho} - \frac{T_s}{m\rho^2\omega_0}\,\omega$$

for ω. With some re–arrangement, we obtain the more concise formulation

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} \;=\; \frac{\omega_\infty - \omega}{\tau}\,, \tag{8}$$

where

$$\tau \;=\; \frac{m\rho^2\omega_0}{T_s} \qquad \text{and} \qquad \omega_\infty \;=\; \omega_0\left(1-\frac{\rho\, mg\sin\theta}{T_s}\right)$$

are the motor spin–up timescale and asymptotic (steady–state) speed.

Example. When $m = 2$ kg, $\theta = 30°$, $r = 0.05$ m, and $N = 50$, the no–stall condition (3) is satisfied, the motor spin–up timescale is $\tau \approx 0.152$ s, and the steady–state motor speed is $\omega_\infty \approx 0.228\,\omega_0$.

The solution to equation (8), subject to the initial condition $\omega = 0$ at $t = 0$, can be written as

$$\omega(t) \;=\; \omega_\infty\,[\,1 - \exp(-t/\tau)\,]\,. \tag{9}$$

If the steady–state analysis is to furnish an accurate run time estimate, the timescale τ should be small compared to the predicted run time (4).

The exact run time, allowing for a non–negligible acceleration phase, can be computed as follows. From (7) and (9), the time–dependent speed of the load up the ramp is

$$v \;=\; \rho\,\omega_\infty[\,1 - \exp(-t/\tau)\,] \;=\; \frac{\mathrm{d}s}{\mathrm{d}t}\,.$$

Thus, if traversal of the ramp length L requires time Δt, we have

$$\rho\,\omega_\infty \int_0^{\Delta t} 1 - \exp(-t/\tau)\;\mathrm{d}t \;=\; \int_0^L \mathrm{d}s \;=\; L\,,$$

or equivalently

$$(\Delta t/\tau) + \exp(-\Delta t/\tau) \;=\; 1 + \frac{L}{\rho\,\omega_\infty \tau}\,. \tag{10}$$

With $z = \Delta t/\tau$, the function $f(z) = z + \exp(-z)$ on the left satisfies $f(0) = 1$ and $f'(z) > 0$ for $z > 0$, so there is a unique positive z for which the value of this function is equal to the expression on the right. The solution can be computed by a simple (e.g., Newton–Raphson) iteration method, using the steady–state value (4) as a starting approximation.

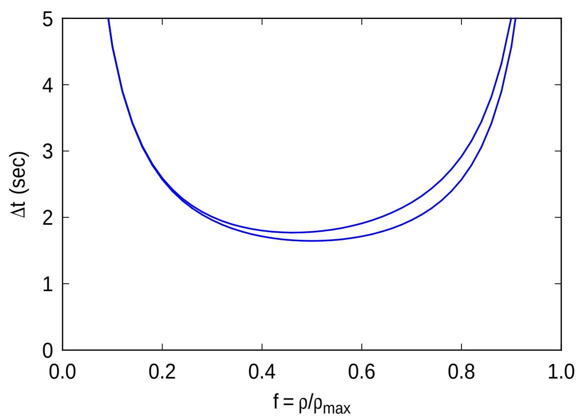

Figure 5: Theoretical run times, as a function of the ratio $f = \rho/\rho_{\max}$, for the case $m = 1$ *shigley*, $L = 0.75$ m, $\theta = 20°$, based on (lower) the steady–state estimate (4), and (upper) solutions of the transient–behavior equation (10).

Figure 5 compares theoretical timings based on the steady–state estimate (4) and the solution to the transient–behavior equation (10), as a function of the ratio $f = \rho/\rho_{\max}$ for the case $m = 1$ *shigley*, $L = 0.75$ m, and $\theta = 20°$. The difference is seen to be relatively minor, but biased toward the higher f values. The key message of this graph is that operating near the limits $n \to 0$ or $n \to n_0$ of the motor characteristic incurs a severe run–time penalty.

Note that the optimum value $f = \frac{1}{2}$ predicted by the steady–state analysis equation (5) is no longer exact if the transient behavior is taken into account.

However, both graphs in Figure 5 are fairly flat for $0.4 \leq f \leq 0.6$, so small deviations about $f = 0.5$ are relatively inconsequential.

5 Project management

At UC Davis, the *Shigley Hauler* project is run on a tight schedule, to conform with the 10–week lecture duration of each quarter. The project is introduced at the beginning of the first week, and the competition is held at the end of the tenth week. This schedule serves to emphasize the importance of proper project planning and management. The student teams are advised to devote equal time and effort (with appropriate division of responsibilities among the team members) to three key phases of the project:

1. *Design and analysis.* A quantitative approach to all aspects of the design and performance analysis of the *Shigley Hauler* is expected — including gear train layout, sizing and mounting of the gear shafts, selection of spool sizes, force and deflection analysis, choice of materials, and the predicted run times. The student teams are advised to complete this phase with 3–4 weeks, and the lectures cover relevant material on gears, bearings, shafts, and DC motors to assist in this. This phase can also be used for the procurement of materials and components required to fabricate the *Shigley Hauler*.

2. *Shigley Hauler fabrication.* Prior machine shop training allows the student teams to immediately begin fabrication of the *Shigley Hauler*, once the design has been completed. In this phase, great emphasis is placed on the precision and robustness of the implementation with regard to considerations such as accurate spacing and alignment of the gear shafts (or provision for adjustment thereof); secure mountings of the gears and spools on the shafts, and of the shaft bearings in the gearbox casing, etc. A cart to securely carry the load is also required, but should be as light–weight as possible. The goal is to have a working device ready for trial tests by the 7th or 8th week.

3. *Testing & troubleshooting.* Issues that were not anticipated in the design or fabrication phases will inevitably arise, so it is critical to have a 2–3 week period to identify and address these problems before the competition. With proper attention to the design and fabrication phases, only minor fine–tuning adjustments should be necessary at this stage, but the 2–3 week testing period allows for substantial changes to correct more significant problems.

6 Competition results

Recent offerings of EME 150B have typically involved 12–16 student teams (see Figures 6 and 7). In order to maintain a reasonable project competition duration (4–5 hours), the test runs are restricted to four cases, namely:

1 *shigley* @ 20°,   2 *shigleys* @ 30°,   4 *shigleys* @ 40°,   5 *shigleys* @ 60°.

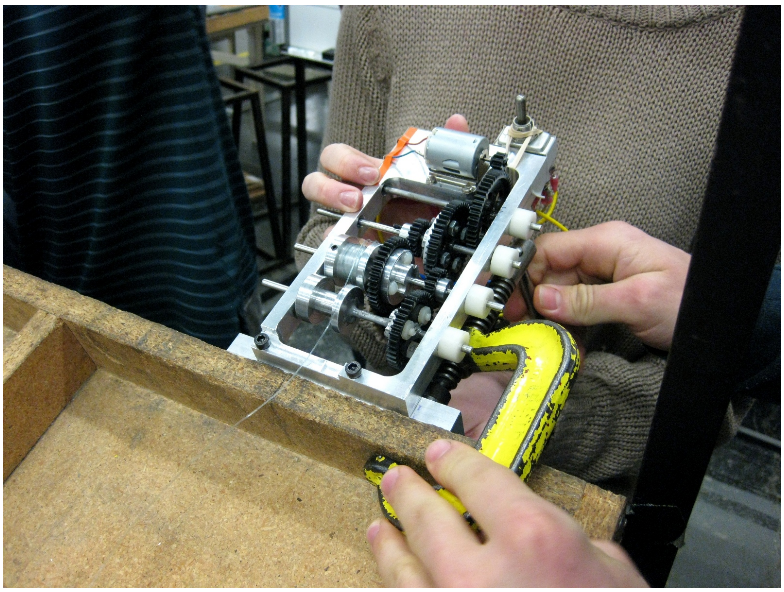

Figure 6: Securing a *Shigley Hauler* to the test ramp with C clamps.

The difficulty of a run employing m shigleys at a ramp angle θ is proportional to $m \sin\theta$, and the above choices correspond to runs ranging from easy to very difficult. The teams are allowed two attempts at each run, the faster of the two timings being recorded. Inevitably, a few teams are still going strong once these "official" runs are completed, and wish to try more challenging cases for bonus points (the most difficult run ever recorded, 8 *shigleys* @ 60°, required several minutes to complete). Timings from a recent representative competition, without bonus runs, are enumerated in Table 1.

For each of the four runs, Table 2 compares the theoretical shortest run time (i.e., the value that minimizes the solution to equation (10) with respect to $f = \rho/\rho_{\max}$) and the best run time actually observed in the competition. The "real–world" timings are seen to be 2–3 times longer than the theoretical minima. Several factors may contribute to this discrepancy, including:

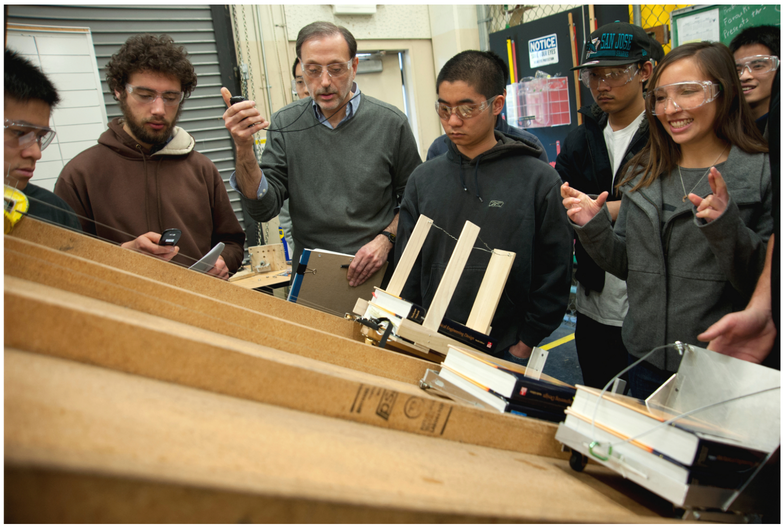

Figure 7: *Shigley Hauler* competition in progress — 2 *shigleys* @ 30°.

team name	1 @ 20°	2 @ 30°	4 @ 40°	5 @ 60°
Algol	12.8 s	15.3 s	———	———
Altair	5.6 s	12.4 s	31.9 s	50.5 s
Antares	9.7 s	27.8 s	73.5 s	———
Betelgeuse	6.5 s	17.3 s	54.2 s	76.9 s
Capella	5.6 s	13.7 s	30.0 s	48.2 s
Electra	8.6 s	20.9 s	59.4 s	———
Maia	9.1 s	21.1 s	54.5 s	———
Mizar	11.6 s	15.4 s	53.0 s	59.2 s
Polaris	7.6 s	21.9 s	53.8 s	69.7 s
Pollux	7.6 s	19.7 s	38.0 s	62.1 s
Sirius	7.2 s	17.9 s	61.4 s	104.1 s
Spica	11.1 s	15.9 s	46.2 s	74.6 s

Table 1: Representative competition results for 12 student teams using runs with 1 *shigley* @ 20°, 2 *shigleys* @ 30°, 4 *shigleys* @ 40°, 5 *shigleys* @ 60° — the blank entries correspond to runs that either stalled or were disqualified.

	1 @ 20°	2 @ 30°	4 @ 40°	5 @ 60°
theoretical	1.7 s	4.7 s	12.0 s	20.8 s
competition	5.6 s	12.4 s	31.9 s	48.2 s

Table 2: Comparison of the theoretical minimum run time, obtained from (10) with $f = \rho/\rho_{\max} = \frac{1}{2}$ and the fastest competition run time from Table 1.

- modest quality of the injection–molded plastic gears;
- imprecise centering, mounting, or spacing of the gears;
- insufficient rigidity or misalignment of the gear shafts;
- the DC motor manufacturer specifications are optimistic;
- depletion of the battery voltage due to prior use or aging;
- operation at sub–optimal values of the ratio $f = \rho/\rho_{\max}$;
- fricitional dissipation at the gear shaft bushings/bearings;
- the additional weight of the cart used to hold the *shigleys*;
- flexure of spool under the load F if the radius r is small.

The competition results clearly illustrate the importance of maintaining tight tolerances and reducing frictional dissipation in efficient power transmission, and of the prototyping and practical verification of mechanical systems — as noted by the celebrated sportsman–philosopher Yogi Berra,

> *In theory, there is no difference between theory and practice.*
> *In practice, there is.*

7 Project grade

A great diversity of *Shigley Hauler* performance is usually evident during the competition — some teams may complete only the first few easy runs, while other teams complete all the "official" runs with excellent timings and insist on demonstrating their engineering prowess through bonus runs. Teams that underperform in the competition may nevertheless have invested considerable effort in the design and fabrication of their device. To avoid unduly penalizing such teams, the overall project grade is divided into three equal parts — (i) participation; (ii) competition performance; and (iii) project report.

Part (i) is automatic for teams that show up to the competition with a credible–looking device. Various quantitative measures have been employed to assess part (ii), with greater weight assigned to the more difficult runs, but qualitative factors such as smoothness and consistency of the *Shigley Hauler* performance are also considered. For part (iii), the report is expected to give a detailed description of the design, analysis, fabrication, troubleshooting, and competition performance of the device, and underperforming teams are advised to give a critical analysis of the causes of underperformance.

8 Learning outcomes & project assessment

To assess the educational impact of the *Shigley Hauler* project, the students were asked to complete an end–of–term questionnaire that seeks to measure its contribution to enhancing their skills in designing, analyzing, optimizing, and testing a mechanical system that addresses a prescribed function. The questions were organized into three sections, based upon (A) issues related to student confidence in the various aspects of engineering design; (B) general course–related questions; and (C) assessing the impact of the *Shigley Hauler* project on understanding design methodology and practice, as follows.

Part A. On a scale from 1 (low) to 10 (high), rate your confidence to ...

1. ... conduct engineering design;
2. ... identify a design need;
3. ... develop design solutions;
4. ... select the best possible design;
5. ... construct a prototype;
6. ... evaluate and test a design;
7. ... communicate a design;
8. ... re–design a system.

Part B. On a scale from 1 (low) to 7 (high), assess the following statements.

1. The *Shigley Hauler* project helped in understanding the course content.
2. It is interesting to learn about the design of machine elements.
3. Fabricating and testing a prototype helped me to understand the design better than just theoretical calculations.
4. I like engineering design projects.
5. I would like to pursue a career that involves innovative design projects.

Part C. On a scale from 1 (low) to 7 (high), rate the *Shigley Hauler* project in terms of better understanding ...

1. ... gear design;
2. ... joint design;
3. ... shaft design;
4. ... DC motor operation;
5. ... bearing design.

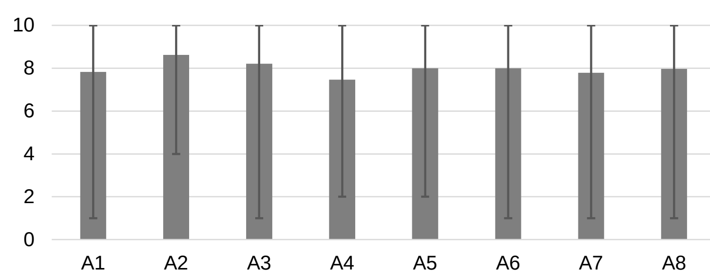

Figure 8: Mean values for responses to the Part A questions, concerned with student confidence in various aspects of engineering design, on a scale from 1 (low) to 10 (high) — the "error bars" indicate the range of the responses.

As can be seen in Figure 8, the responses to the Part A questions show that most students are quite confident they can conduct key design tasks. In particular, they feel most confident in their ability to identify a design need and to develop design solutions, with mean scores of 8.62 and 8.21 out of 10. They have least confidence in their ability to select the best possible design, but this point nevertheless yielded a relatively high score of 7.46 out of 10. This aspect of the design process is not stressed in EME 150B due to time constraints, but it is covered in the capstone design class.

The students were also positive in their responses to the Part B questions (see Figure 9). The highest mean scores were for the two statements B5: "I would like to pursue a career that involves innovative design projects" (6.69 out of 7), and B4 "I like engineering design projects" (6.66 out of 7) — the responses to these prompts also had the smallest standard deviations.

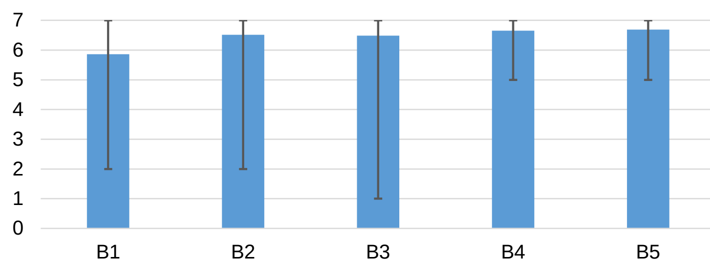

Figure 9: Mean responses to the Part B questions, on a 1 (strongly disagree) to 7 (strongly agree) scale: the "error bars" indicate the range of responses.

Figures 10–12 present more detailed breakdowns of the responses to the statements B2, B3, and B5. The majority of the students find it interesting to learn about the design of machine elements (Figure 10), and the course may have reinforced their motivation to pursue careers in the mechanical design field (Figure 11). Also, 69% of the students strongly agree that "fabricating and testing a prototype helped in understanding the design better than just theoretical calculations" (Figure 12). The mean score for this statement was 6.48 out of 7, with a standard deviation of 1.18.

Finally, the Part C questions asked the students to reflect on the value of the *Shigley Hauler* project in enhancing their understanding of the design of basic machine components (Figure 13). The highest scores were 6.14 out of 7 for gear design, and 6.03 out of 7 for shaft design, which are central aspects of the project. The lowest score, 5.21 out of 7, was for joint design, a topic that is of relatively marginal importance for the project.

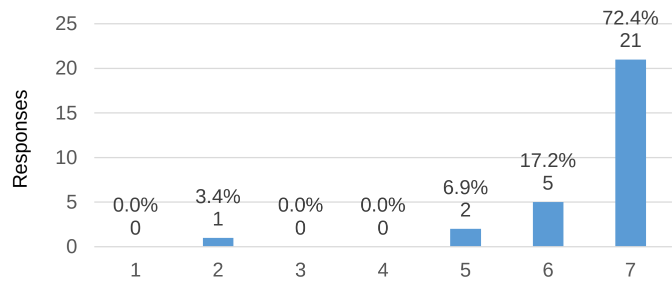

Figure 10: Prompt B2 “It is interesting to learn about the design of machine elements” responses, on a 1 (strongly disagree) to 7 (strongly agree) scale.

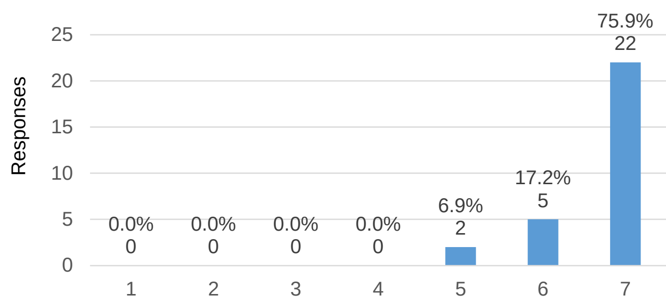

Figure 11: Responses to prompt B5 “I would like to pursue a career that involves innovative design projects” on a scale from 1 to 7.

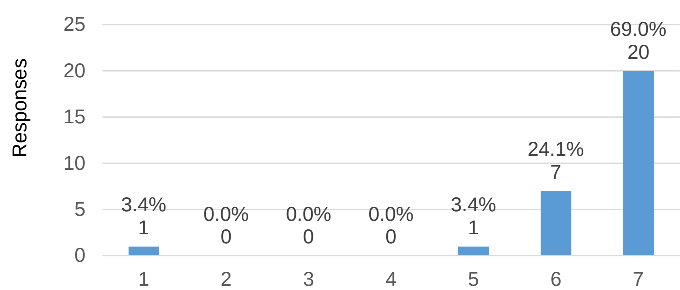

Figure 12: Prompt B3 “Fabricating and testing a prototype helped me to understand the design better than just theoretical calculations” responses, on a scale from 1 (strongly disagree) to 7 (strongly agree).

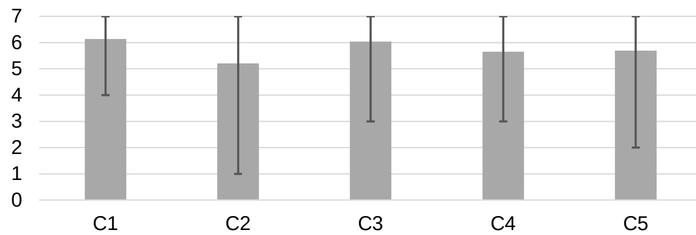

Figure 13: Mean responses to the questions in Part C, concerned with the educational value of the *Shigley Hauler* project, on a 1 (strongly disagree) to 7 (strongly agree) scale: the "error bars" indicate the range of the responses.

In summary, the results show that *Shigley Hauler* project is very effective in improving student motivation and understanding of core mechanical design principles, and motivating students to pursue careers as design engineers.

9 Conclusion

Through classroom testing over several years, the *Shigley Hauler* project has proven to be highly successful in significantly improving student motivation and understanding of machine design principles. The project is amenable to completion within a relatively short timeframe, at modest cost, and serves to emphasize the importance of teamwork and time management in the context of system design, prototyping, and verification. The strong dependence of the *Shigley Hauler* performance on maintenance of tight tolerances and accurate alignments highlights the importance of precision engineering principles. The project also serves to illustrate some key paradigms of concurrent engineering, such as design for manufacturability, and the potential need for iterations between design, analysis, prototyping, and testing.

References

[1] R. G. Budynas and J. K. Nisbett, *Shigley's Mechanical Engineering Design* (10th ed.), McGraw–Hill, New York, ISBN 978–0–07–339820–4, 2015.

[2] W. Cheng, X. Wu, Z. Zhang, F. Liu, M. Zhang, and P. Guo (2013), Effective project–oriented approach for training professional mechanical engineers in undergraduate education, *International Journal of Mechanical Engineering Education* **41**, 289–296.

[3] D. Kelley (2015), Peer evaluation within a team design project, *Journal of Engineering Technology* **32**, 44–50.

[4] T. J. Moore, M. M. Hynes, S. Purzer, A. W. Glancy, E. A. Siverling, K. M. Tank, C. A. Mathis, and S. S. Guzey (2014), STEM integration: evidence of student learning in design–based curricula, Proceedings, 2014 IEEE Frontiers in Education (FIE) Conference, 1–7.

[5] W. Singhose, J. Vaughan, and R. Mayor (2009), Use of design competitions in mechatronics education, Proceedings, 2009 IEEE International Conference on Mechatronics, DOI: 10.1109/CMECH.2009.4957226.

[6] D. A. Tolbert and S. R. Daly (2013), First–year engineering student perceptions of creative opportunities in design, *International Journal of Engineering Education* **29**, 879–890.

[7] R. D. Weinstein, J. O'Brien, E. Char, J. Yost, K. R. Muske, H. Fulmer, J. Wolf, and W. Koffke (2006), A multidisciplinary, hands–on, freshman engineering team design project and competition, *International Journal of Engineering Education* **22**, 1023–1030.

[8] `http://www.mabuchi-motor.co.jp/cgi-bin/catalog/e_catalog.cgi?CAT_ID=re_280rasa`

[9] `http://www.jameco.com/webapp/wcs/stores/servlet/Product_10001_10001_1810072_-1`