Rail Rider

Source: Kabelleger / David Gubler (CC BY-SA 3.0)

Prepared for MECH 223

Prepared by Peter Ostafichuk, Agnes d'Entremont and Markus Fengler

Department of Mechanical Engineering

The University of British Columbia

January 4, 2018

ABSTRACT

The first MECH 223 project, Rail-Rider, is to design a prototype cargo-carrying train that can quickly and safely climb and descend on complex tracks for a client (fictitious company named *Lectro-Rail*). Each team will design and construct their own autonomous train locomotive capable of hauling standard cargo cars while ascending/descending under automatic control. They will operate their locomotive in a class-wide competition on a 3D track layout. Based on the outcome of the competition and what was learned throughout the development process, they will provide clear recommendations to *Lectro-Rail* on which one of the 20 competing designs to adopt. Locomotive functions will include the ability to traverse a range of track topography, haul cargo cars, ascend steep hills, and control speed to stay on the track. The locomotive should also possess the attributes of high speed, low cost, and a pleasing aesthetic.

The primary learning focus of the project is to become familiar with a process for developing a design which best fulfills a particular set of desired characteristics within a given set of constraints. Emphasis will be on methods of concept generation, concept evaluation, and prototyping. The key deliverables to be submitted for this project will include:

- A project poster for display to a public audience highlighting the team's design process and highlighting the spacecraft features and attributes.
- A prototype locomotive for the competition developed using the design tools introduced throughout the course.
- A team technical oral presentation to instructors (MECH 223 and MECH 226) and classmates that presents the team's design project to a mixed audience (clients who may not have technical depth in this area, and engineers who may) and includes a summary of the analytical work leading to the design solution.
- A formal technical report with recommendations to the (non-technical) client, due after the competition, outlining the team's competition locomotive development process, a critical review of the competition and what was learned, and providing specific recommendations to the client on the best next steps to take with the project to develop a locomotive able to quickly and safely move cargo.

Project information is generally outlined in this project description, however additional information will be provided on Connect and distributed in class.

TABLE OF CONTENTS

ABSTRACT I
LIST OF TABLES IV
LIST OF FIGURES V
1.0 INTRODUCTION 1
2.0 BACKGROUND: THE BENEFITS AND PERILS OF RAIL TRANSPORT 1
2.1 Benefits of Rail 1
2.2 Drawbacks 2
2.3 Perils 3
3.0 PROJECT OVERVIEW 4
3.1 Project Synopsis 4
3.2 Project Format 5
3.3 Integration with MECH 226 5
3.4 Group Formation 5
4.0 COMPETITION DETAILS 6
4.1 Track Layout 6
4.2 Competition Round Overview 7
4.3 Optimized Locomotive Quantities 10
4.4 Competition Procedure 11
4.5 Competition Scoring 12
4.6 Competition Restrictions 14
5.0 PROJECT CONSTRUCTION DETAILS 17
5.1 Deliverables 17
5.2 Materials 17
5.3 Bill of Materials 18
5.4 Student Shop Access, Toolkits, and Other Details 20
6.0 CONCLUSION 22
APPENDIX – COMPETITION SCORING DETAILS 23
A-1 Base Score (B_i) 24
A-2 Aesthetics Score (LC_A) 25

A-3 Locomotive Cost Criterion Score (LC_C) 25
A-4 Locomotive Energy Criterion Score (LC_E) 26
A-5 Cargo Transport Rate Criterion (PC_C) 27
A-6 Derailment Performance Criterion (PC_D) 28
A-7 Speed Performance Criterion (PC_S) 28
A-8 Time Delay Penalty Performance Criterion (PC_T) 29
A-9 A Closing Note on Requirements and Evaluation Criteria 30

LIST OF TABLES

Table 1 - Project Deliverables 17
Table 2 - Sample Bill of Materials Entries 19

LIST OF FIGURES

Figure 1. Representative Track Layouts 4
Figure 2. Round 1 Track Profile 6
Figure 3. Rounds 2 to 5 Track Layout 7
Figure 4. Round 2 and 3 Track 8
Figure 5. Round 4 Track 9
Figure 6. Round 5 Track 10
Figure 7. Base Score Checkpoints and Gates 24
Figure 8. Cost Criterion Score 26
Figure 9. Energy Criterion Score 27
Figure 10. Cargo Transport Rate Performance Criterion Score 27
Figure 11. Speed Performance Criterion Score 29

1.0 INTRODUCTION

This year's first MECH 223 design project is based on the transportation of cargo using trains. The fictitious client, *Lectro-Rail* is interested in exploring battery-electric locomotives as an economical and environmentally sensitive way to replace the some of the diesel-electric locomotives that are currently used. *Lectro-Rail* is sponsoring a prototype development project and your team is one of 20 competitors. Your project focuses on modelling the deployment and operation of a locomotive that can pull cargo cars and safely and quickly negotiate complex track layouts. This document provides an orientation to the project and outlines some of the specifications for the prototype locomotive. Guidelines for the development of other course-related deliverables, including the logbook, an early focused physical prototype, the poster presentation, the recommendation report and the oral presentation, can be found in separate documents provided on the course Connect site.

The document sections are arranged as follows:

- Section 2: Project Description
- Section 3: Competition Objectives
- Section 4: Project Construction Details

An appendix provides detailed information on the competition scoring system.

2.0 BACKGROUND: THE BENEFITS AND PERILS OF RAIL TRANSPORT

Transportation is the second largest source of greenhouse gas (GHG) emissions in Canada and accounts for approximately one-quarter of Canada's total GHG emissions: freight transportation accounts for almost 45% of this sector (Environment and Climate Change Canada, 2017). In fact, as other sectors (such as electricity generation and heavy industry) have reduced their total emissions, total transportation emissions have increased by 40% between 1990 and 2015. During the same period, the total emissions associated with freight trucking has more than tripled, negating any gains from the growing use of hybrid and electric passenger cars. Rail is one of the most energy efficient means of freight transport and fully electric rail is cleaner than diesel electric. Extensive track infrastructure in many parts of the world makes it impractical to provide electric power e.g. via overhead conductors as is done in some parts of Europe, so *Lectro-Rail* is proposing to use battery-driven locomotives. To meet expected stricter environmental demands associated with global agreements like the Paris climate accord, heavier use of freight rail transportation may be one way to improve national environmental performance. Although railway transport is attractive from both environmental and economic perspectives, there are limitations and hazards with rail. The benefits and risks involved with rail transport are described further below, and form the basis for the first MECH 223 design project.

2.1 Benefits of Rail

Railways provide the most economical method of moving containers and bulk commodities over great distances (Transport Canada, 2005). On average, rail uses 80% less energy per tonnekilometre than intercity tractor-trailer trucks and almost 90% less energy than large trucks (trucks over 14970 kg) (Railway Association of Canada, 2001). In Canada, rail carries roughly 70% of the surface cargo (measured in tonne-kilometres) yet contributes only 3% to the total GHG emissions generated by transportation (Railway Association of Canada, 2010). In contrast, road transport represents only about 30% of the surface cargo volume (in tonne-kilometres) but generates 32% of the total transportation GHG emissions (Railway Association of Canada, 2003). In absolute terms, the total volume of cargo transported by rail in Canada is roughly 300 billion tonne-kilometres and contributes approximately 6 megatonnes of GHG emissions (Padova, 2005).

The increased efficiency in rail transport is due to a number of factors. Most notably, the rolling resistance of a steel wheel on a steel rail is significantly less than an inflated rubber tire on a road surface. The typical automobile tire has a rolling resistance of about 0.010 times the vehicle weight; truck tires, inflated to much higher pressure, typically have a rolling resistance of about 0.007 times the truck weight. In contrast, the rolling resistance of a steel wheel of a fully loaded railway freight car is approximately 0.001 times the car weight. (Lawyerwheel, 2004). Further gains in efficiency are due to the reduced aerodynamic resistance per unit volume of a long train compared to a truck. This results from the reduced average speed of the train (aerodynamic drag increases with speed squared) and the increased length to frontal area ratio of the train (considering the total length, a train is much more streamlined than a truck). Other factors, such as the reduced acceleration and deceleration of a freight train compared to a truck, as well as the reduced average gradient, both uphill and downhill, of rail compared to road also contribute to greater rail transport efficiency.

Analysis of the full social cost of surface cargo transportation – including factors such as pollution, accidents, traffic congestion, noise, and road maintenance – greatly favour rail over road. The social cost per million tonne-km has been estimated at $3,296 for rail versus $34,664 for road. Based on the volume of surface cargo carried in Canada, with the above analysis it has been proposed that a shift to increased rail utilization could result in a net annual social cost savings of $673 million (McKinstry and Bounajm, 2010).

2.2 Drawbacks

The economic and environmental benefits that come with increased energy efficiency of rail transport are offset by several drawbacks. The creation and maintenance of a dedicated rail line is a capital-intensive venture. As a result of this high cost and the very small number of direct users of railways, there are only a small number of rail lines; transport routes are fixed and limited compared to the road network. (However, rail can still form the backbone for an intermodal transportation system where goods are transferred between rail and road as needed.) From an operational point of view, train speed is limited on tracks with turns in order to prevent derailments; in other words, the turn radius largely determines the maximum speed of a train negotiating that turn. Likewise, the track gradient limits the type and speed of trains that can operate on that line; on uphill gradients, the train is limited by power and frictional (gripping) considerations, and on downhill gradients the train is limited by deceleration and braking considerations. Both the turn and gradient considerations are more restrictive for rail than for road and can therefore significantly limit rail transport speed compared to road transport.

2.3 Perils

When a train derails, the effects can be catastrophic. One recent derailment of a train with over 7 million litres of crude oil caused the Lac-Mégantic rail disaster. After a small emergency on board, some equipment which was needed for brake operation of the freight train was shut down, and eventually the train started rolling down the descending grade it was parked on. The following is from the incident report of July 6, 2013.

> *As it moved down the grade, the train picked up speed, reaching a top speed of 65 mph. It derailed near the centre of the town at about 1:15 a.m.*
>
> *Almost all of the 63 derailed tank cars were damaged, and many had large breaches. About six million litres of petroleum crude oil was quickly released. The fire began almost immediately, and the ensuing blaze and explosions left 47 people dead. Another 2000 people were forced from their homes, and much of the downtown core was destroyed.* (Transportation Safety Board, Government of Canada, 2014).

This particular incident drew a great deal of media attention, but there have been many other recent high-profile derailments. Another example is the Amtrak Cascades passenger train that derailed on December 19, 2017, just south of Seattle.

Transport Canada reports the average number of derailments per year in Canada, for the decade between 2007 and 2016, to be approximately 670 (based on data from Transportation Saftey Board, 2016).

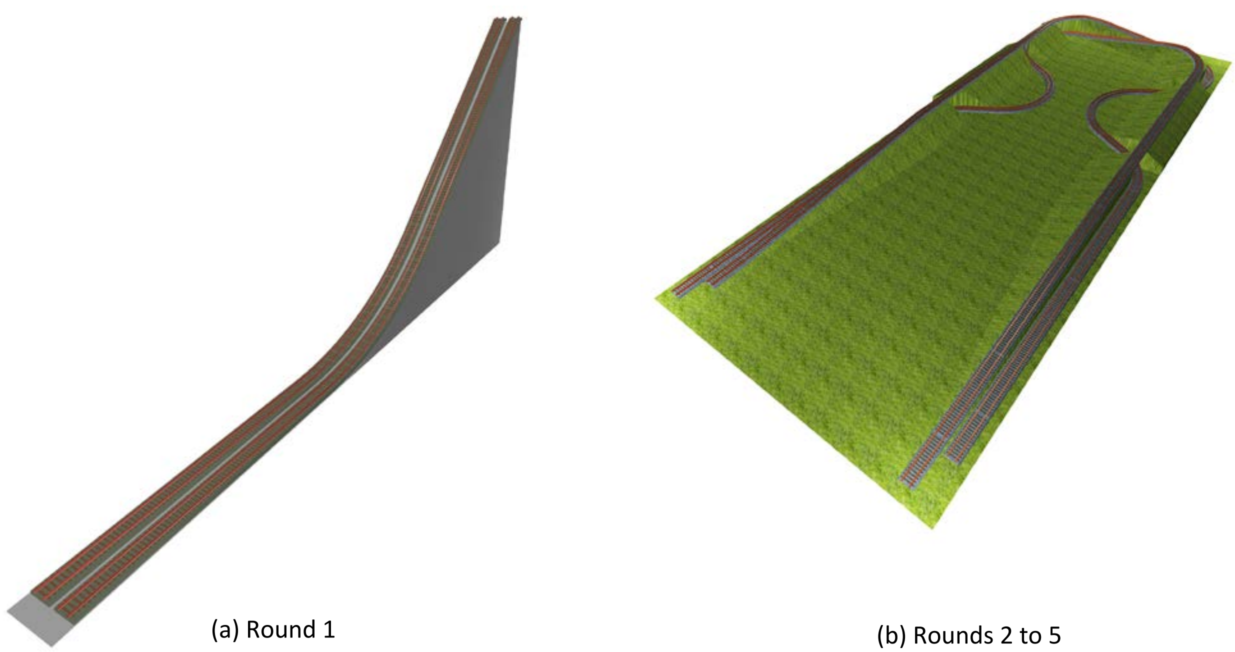
If the speed limitations of rail could be relaxed while at the same time reducing the occurrence of derailments, railways could be further developed as an energy-efficient and environmentally-friendly form of freight transport.

3.0 PROJECT OVERVIEW

For this project, teams will explore the design and operation of an improved vehicle for battery driven electric rail transportation of cargo. A synopsis of the project is provided below. The sections that follow outline the format of the project within MECH 223, the integration with MECH 226, and group formation details.

3.1 Project Synopsis

This year's first MECH 223 design project will explore the opportunity for an engineering solution to improve rail transportation of cargo. In particular, teams will design and construct an autonomous locomotive to be connected to supplied rail cars (hereafter collectively referred to as the "train") for operation on representative rail segments in treacherous terrain. We will limit scope to conventional (i.e. adhesion) freight railway systems—that is, systems where the train contacts only the rail and relies on gravity to stay on the tracks. In other words, systems such as used on steep terrain systems such as rack railways, cable cars, and funiculars and designs that clamp to the rails will not be permitted. The objective is to be able to run on conventional tracks without need for modification of the tracks so that it can be shared by conventional trains. Another objective is to maintain the environmental benefits of rail transport (that is, low energy input) while addressing the speed limitations of rail in terrain with tight corners and large gradients and at the same time ensuring that cargo is delivered safely and on time. The project will culminate in a competition where teams operate their train on various tracks mounted to an 8′×20′ platform (hereafter referred to as the "playfield"), with the objective of safely reaching predefined locations. Figure 1 below shows a graphical representation of possible track layouts for the various rounds of the competition—the actual competition tracks may be different. In all rounds, two mirror-image, identical tracks will be utilized so that two teams can compete simultaneously. Additional details about the tracks are provided in Section 4.1.



(a) Round 1

(b) Rounds 2 to 5

Figure 1. Representative Track Layouts

3.2 Project Format

The project is conducted over a four-week period and will conclude with a competition including a poster presentation followed two days later by a technical oral presentation to class instructors (MECH 223 and MECH 226) and peers, and submission of a technical report with formal recommendation for a fictitious client. The technical aspects of the project are based primarily on the engineering science material from MECH 221 (there will be a second, three-week project in the second half of MECH 223 based more directly on the material from MECH 222). In addition to the major end-of-project deliverables, there will be other deliverables throughout the four weeks to ensure that teams stay on task and have a good chance of success at the competition. There are also various scheduled activities during the four weeks to help guide teams through the project.

3.3 Integration with MECH 226

The poster presentation, oral presentation and formal report that each team prepares for the project will also serve as materials for the MECH 226 (technical communication) course. An evaluation of the technical content in these items will apply towards MECH 223 grades, while the MECH 226 instructor will assess the effectiveness of the communication. Students not registered in MECH 226 must still work with their group on these tasks in order to receive a grade for MECH 223.

3.4 Group Formation

Work on this project will be done in the assigned course teams of six or seven students. The teams were formed based on information from the MECH 223 Team Formation Survey and from performance in Term 1. All efforts have been made to form teams that have an equitable distribution of skills and abilities, as well as access to tools and transportation. Where possible, students were grouped with others living in the same geographic region of Metro Vancouver.

There are 20 teams in total. The teams have been split into four divisions (five teams in each) named after famous engineers, scientists, and designers: **A**rchimedes, **B**ernoulli, **C**urie, and **D**a Vinci. The divisions will play a similar role as the sections in MECH 220 and 221 did except increased collaboration within a division will be encouraged. Each team will be graded on individual performance and there will be bonuses awarded if all teams in a division perform well relative to the rest of the class.

Teams within a division are encouraged to work collaboratively. For example, teams may choose to develop a division-wide solution for mechatronic elements. Keep in mind any such solutions must be compatible with the designs and strategies of all teams in a division.

4.0 Competition Details

The competition will consist of four individual rounds, plus one division bonus round. Each round will challenge different aspects of train performance. The prime objectives are as follows:

- Round 1: Hill climbing ability
- Round 2: Speed over flat track
- Round 3: Uphill cargo hauling
- Round 4: Traversing dangerous track
- Round 5 (bonus): Division relay race

Details on each round are outlined below. The score the team receives for each round will be determined based on a combination of level of completion, performance, and vehicle parameters defined in the scoring. Full details on track layouts, optimized quantities, scoring system, competition procedure, and competition restrictions are outlined below.

4.1 Track Layout

The competition tracks will be placed on an 8′×20′ playfield (tilting platform). The track will consist of commercially-purchased G scale track (often referred to as "garden railway") with a distance between the rails (also called gauge) of approximately 1.78″. The actual gauge of the track in any location may range from 1.68″ to 1.88″. Efforts will be made to minimize bumps and discontinuities at track joints, but teams should anticipate some such imperfections may be present. A section of sample track will be made available for measurements.

For Round 1 (hill climb), the track will be straight and approximately 15′ in length, and it will be divided roughly into three equal segments: a flat segment with no slope, a smoothly increasing upward curve, and a constant slope section inclined at approximately 45˚. See Figure 1 (a) and Figure 2.

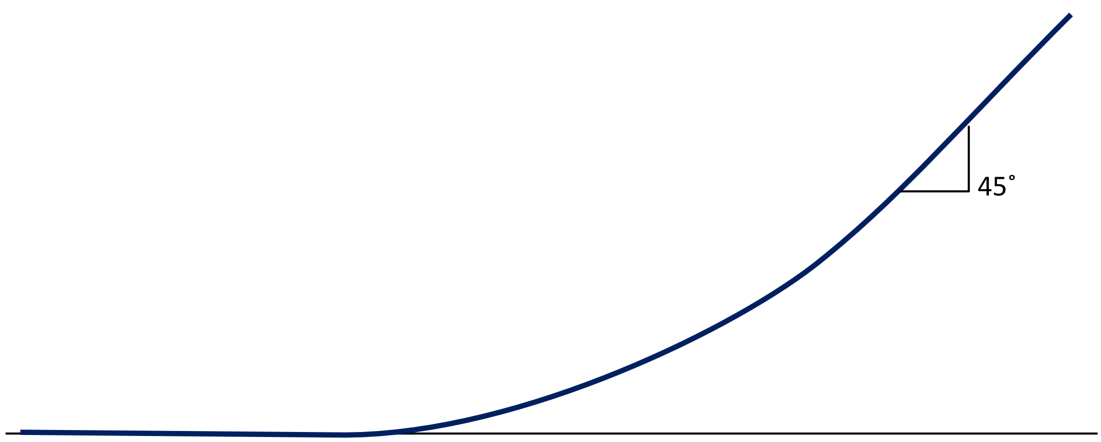
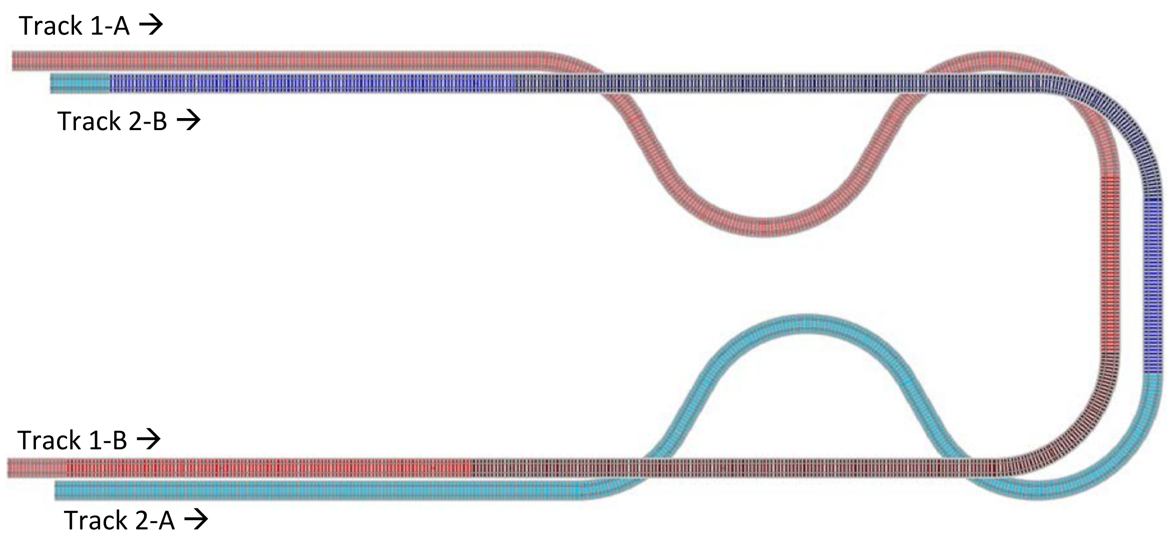


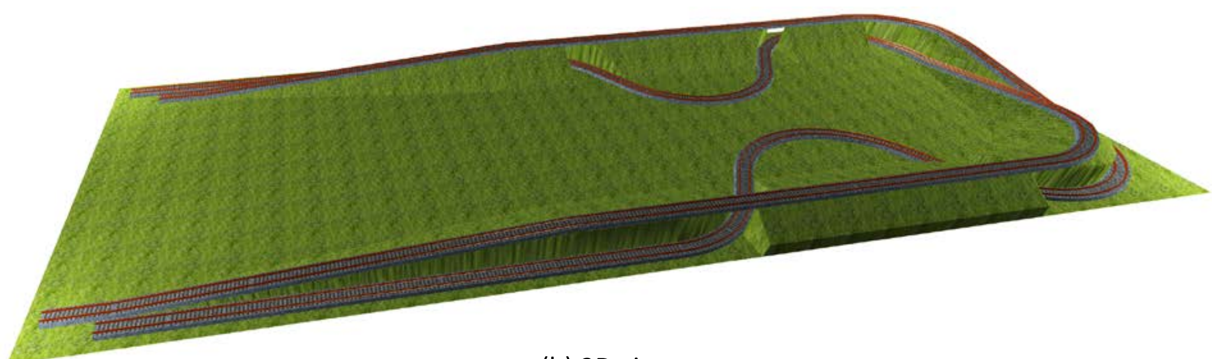
Figure 2. Round 1 Track Profile

Rounds 2 to 5 will take place on different segments of two interleaving, mirror image tracks. Two teams will be able to compete simultaneously on different tracks on the playfield. Rounds 1 and

2 will be completed with the playfield level, and Rounds 3 to 5 will be completed with the table inclined by between 2 and 8° (with the start region lower). The radius of curvature for horizontal curves (that is, bends within the plane of the playfield), as measured to the track centre, will be approximately 24″. Transitions in elevation will have smooth transitions (unlike the abrupt transitions shown in Figure 3 (b)) with a radius of curvature no less than 24″.



(a) 2D layout



(b) 3D view

Figure 3. Rounds 2 to 5 Track Layout

A small 4′×8′ prototyping table, using the same type and gauge of track as for the competition, will be provided in KAIS 1180 near the start of the project for testing and prototyping.

4.2 Competition Round Overview

An overview of Rounds 1 to 5 is provided below. Full scoring details can be found in the appendix. Teams will be assigned a track (1 or 2) and will position their locomotive or train in the designated starting area of that track. A laser photointerupter (i.e. "light gate") will denote the start line on a track. Two teams will compete at the same time and will be given a start signal to indicate the start of the timing clock. Teams may not break the beam of the light gate before the start signal, otherwise a false start will be declared. Additional light gates will be positioned at other locations on the track to measure progress, speed, elapsed time, and other factors important to scoring each round. Further details on the timing gate uses, required vehicle specifications, and false starts can be found in Sections 4.5 and 4.6. Details specific to each round are provided in the sections that follow.

Round 1 (Hill Climbing Ability)

Round 1 will test the ability of your locomotive (no freight cars) to climb a steep hill. The track to be used is depicted in Figure 1(a) and Figure 2, and for this round, it will be placed in the middle of the playfield. The objective is to have your locomotive climb as high as possible up the track, while contacting only the rails in the same manner that conventional locomotives do (i.e. no clamping onto the rails, no touching down on any other portion of the table, rail ties, etc.). The score will be based on how high your locomotive can climb within a 2-minute time limit. The highest track elevation reached by the centre of gravity of your locomotive (you are required to indicate the CofG clearly on your vehicle) will be used to determine your score, relative to the highest track elevation for all teams in the class. You may attempt the hill as many times as you wish in the 2-minute time limit; however, beginning a new attempt will reset your score on the round to zero.

Round 2 (Speed Over Flat Track)

Round 2 will use the flat winding portion of the track ("Track A" in Figure 3) and will test the ability of your locomotive to quickly travel from the start of the track to the finish at the base of the hill (see Figure 4, Round 2 Finish). The playfield (and hence track) will be level in this round, and there is no cargo car to be hauled. The score will be based on how far along the track you travel, and how quickly you are able to move from start to finish relative to the fastest time for all teams in the class. Again, your locomotive must only contact the rail as a conventional locomotive and may not clamp to the rails or touch down on surfaces other than the rail.

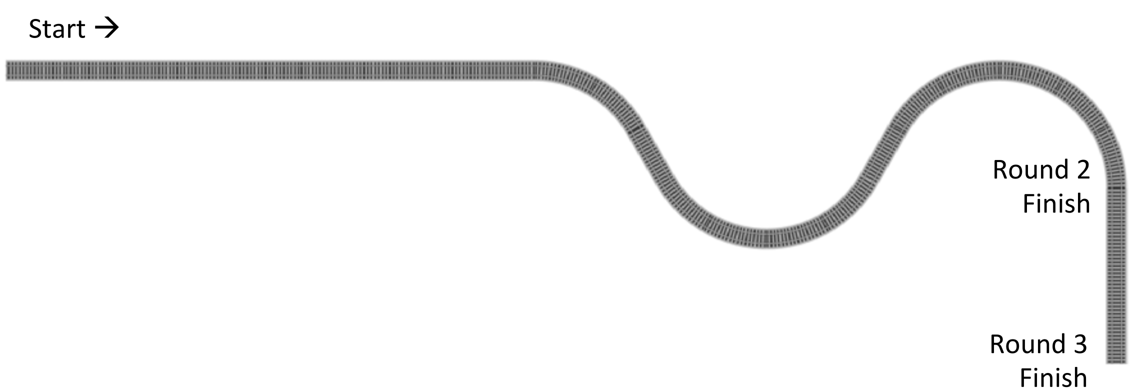


Figure 4. Round 2 and 3 Track

Round 3 (Uphill Cargo Hauling)

The objective of Round 3 is to transport as much cargo as quickly as possible in a single pass on the same track segment as Round 2. Your team will select how much cargo is to be loaded into the freight cars. Two differences in this round are that the playfield will be inclined upwards from the start by between 2˚ and 8˚, and the finish line will be at the top of a steep hill (~10˚). (Note that the playfield inclination combined with the uphill section before the finish line results in the track on some portions of the curves and near the finish line being tilted towards the start.) The score will be based on how far along the track you travel, and your cargo transport rate from start to finish relative to the maximum transport rate for all teams in the class. The cargo transport rate is the amount of cargo divided by the time to travel from start to finish; to maximize this you will need to balance cargo carried and speed.

Round 4 (Traversing Dangerous Track)

In Round 4 you will again try to maximize cargo transport rate by pulling loaded freight cars, but this time it will be done across a particularly dangerous section of track ("Track B" in Figure 3). The playfield will be at the same incline as in Round 3. You will begin at the start. At the end of the straight section of track will be a speed checkpoint (see Figure 5) that will measure your locomotive's speed. Your goals are to maximize measured speed at the checkpoint and to maximize cargo transport rate from the checkpoint to the finish line, at the base of the hill. For maximum score, your entire train and cargo must remain on the track including following the finish line (marked "runout" section).

Figure 5. Round 4 Track

Round 5 (Bonus: Division Relay Race)

Round 5 is a division bonus round in which all five teams from a division will work collaboratively to earn a bonus score for their division. Each team from a division will participate on the same track, but travelling in two different directions (referred to as Track A in one direction and Track B in the opposite direction, see Figure 6). Teams from one division will compete against another division in an elimination relay race. The first team of a division will release locomotives one at a time in opposing directions on the same track. i.e. they will release the first locomotive on the start for Track A, and will try to reach the Track A finish (i.e. the Track B start), as shown in Figure 6. Once the first locomotive reaches the finish line or otherwise stops moving (i.e. becomes stuck or derails), the second locomotive can start on Track B to reach the Track B finish line. The round will continue in this fashion until all locomotives in a division have attempted the round, and then the timer will stop. At the same time, the competing division will operate their locomotives on the mirror track (Track 2 in Figure 3(a)).

Each locomotive will receive 1 point for moving across the start line, 1 point for reaching the transition region (see Figure 6), and 3 points for reaching the finish. If a locomotive becomes stuck or derails, it may be removed from the playfield by the team. This gives a maximum of 5 points per locomotive, and 25 points per division. The division with the most points in the head-to-head will win the relay. If the two competing divisions tie in points, the division with the faster time will win. The winning divisions from the first two head-to-head relays will then compete, as will the two losing divisions from the first two relays. This will determine overall rankings and the scores for the round.

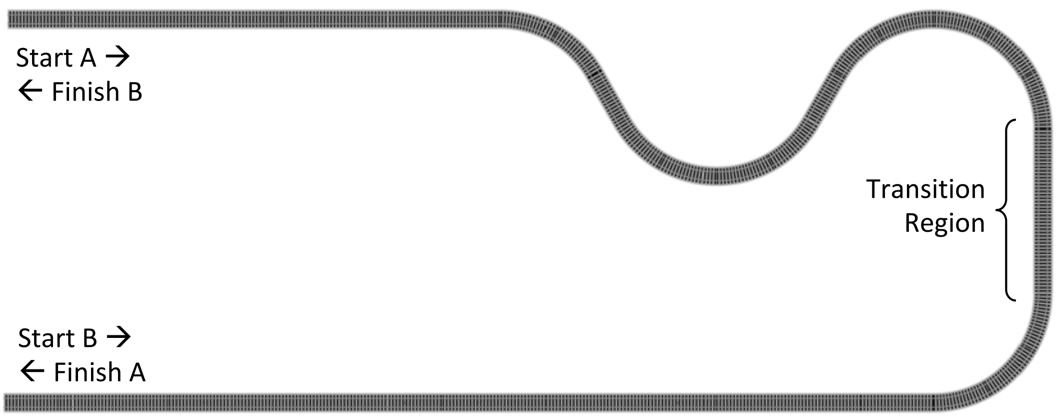


Figure 6. Round 5 Track

4.3 Optimized Locomotive Quantities

In addition to achieving the objectives described above for each round, there are a number of quantities that teams will try to optimize. Each of these quantities is described below with the effects on the final score detailed in Section 3.4.

1. **Cost** is always a factor in engineering design. In this project, the cost of goods of the locomotive based on standardized cost of components and materials will factor into the final score. Labour and engineering costs are being ignored. It doesn't matter whether you get your parts for free or buy them, the project cost of goods is the same. Minimizing cost of goods is desirable, if all other factors remain equal. A detailed bill of materials and cost analysis will be required.

2. **Energy** required to operate the locomotive relates directly to fuel costs and GHG emissions. For this project, energy required will be measured by the number of AA NiMH batteries are used to power the drive system of the locomotive. Energy from other batteries used to power control electronics and other circuits where the energy from the batteries is not used to power the drive system will not count towards energy used.

3. **Aesthetics** refers to the emotional response to sensory information. In this case, this is not about your locomotive looking *nice*, but rather conveying important qualities of your design philosophy and process. Does it look well-designed, fast, powerful, durable, and so on. In this competition, classmates and the public will be invited to vote locomotive aesthetics, and scores will be adjusted based on votes received.

4.4 Competition Procedure

All teams must be ready at the designated start time. One team will be chosen at random to go first in the competition and then subsequent teams will follow in order by increasing division first and then by increasing team number. Penalties apply for teams that are not ready to go when called upon. The playfield will have two tracks for each round, and two teams will compete simultaneously. Teams will change tracks (right or left) between rounds. If Team A2 was drawn to go first in Round 1 from Track A, Team B2 would go at the same time from Track B. Teams C2 and D2 would be waiting in a staging area, and would move to the start area as soon as Teams A2 and B2 cleared the track.

For Round 2, the first team to compete will increase by two team numbers from Round 1. Following the example above, Team A4 would start Round 2 from Track B while Team B4 would be on Track A. For Round 3, Team A1 would start from Track A, and Team A3 would start Round 4 from Track B.

Each team will be permitted to redo any one round of their choice in the competition. This makes one event of a hardware malfunction, faulty launch, faulty deployment or an occurrence of unexpected behaviour on the playfield surface less devastating to the final score. The score in a redo round will be 75% of that which would be earned otherwise (that is, there is a 25% penalty for the redo). A team that chooses to take a redo forfeits any points scored earlier (even if the original score was higher). It will be up to individual teams to decide which round they would like to redo (if any) and they must alert the course instructors of their intent *before* it is announced that the round has ended. Once all teams have completed their first attempts at a round, any teams wishing to redo the round will do so according to the original team order. Subsequent rounds will proceed as scheduled. If a team was not ready within the time limit when called to the first attempt, they can delay for a postponed attempt at the end of the round, but this will either count as the redo or, if a team has already used their redo, the score will be reduced by 50%. Any team that fails to deploy for the postponed attempt within the allotted start time will forfeit that round.

In Round 5, all five teams in a division will collaborate and be on the playing field simultaneously, competing against the five teams from a second division. The two divisions with the highest combined scores at the start of Round 5 will go first, followed by the division with the next highest combined score, and so on.

For all rounds, when it is a team's turn to compete, they will have two minutes from the time they are called to set up in the starting area and release their locomotive. After two minutes, a linearly increasing penalty will be applied starting at 0% at two minutes and increasing to 100% after four minutes. In other words, a team that does not release their locomotive until four minutes or more after their turn starts will receive a score of zero for that round.

4.5 Competition Scoring

A brief summary of the scoring system for the competition is outlined in this section; complete scoring details are provided in the Appendix. Scoring of the project is based on the combination of three main elements: base score (*B*), performance criteria score (*PC*), and locomotive criteria score (*LC*).

Base Score (B)

The base score in each round will be determined as follows:

- Round 1 (B_1): points awarded based on the maximum elevation reached by the locomotive relative to other teams
- Rounds 2, 3, and 4 (B_2, B_3 and B_4): points awarded based on how far along the track the locomotive is able to travel
- Round 5 (B_5): The Round 5 scoring is discussed separately in the Appendix.

The base score will be multiplied by a series of evaluation criteria; these consist of performance criteria and locomotive criteria, as described below.

Performance Criteria Scores (PC)

The performance criteria below are used to modify the base score in each round.

- Derailment penalty (PC_D) – a penalty of 0.5 will be assessed in Rounds 1 to 4 if a locomotive, or any rail cars hauled by the locomotive, derail (i.e. leave the rails permanently). It is not necessary for part of the train to contact the playfield surface to qualify as a derailment. If the wheels of a train temporarily lift from the rails but the train rights itself and the wheels again properly contact the rails, this will not be considered derailment.
- Cargo transport rate (PC_C) – in Round 3 and Round 4, a score will be determined based on the rate of cargo transport (units/second) for teams that successfully complete round objectives. The score will sinusoidally increase from 0.5 for no cargo transported to 1 for maximum cargo transport rate for the class. Trains that do not complete round objectives will automatically receive a score of 0.5. In Round 3, the cargo transport rate will be determined between the start line and finish line. In Round 4, the average speed will be determined between the checkpoint at the top of the hill and the finish line at the bottom of the hill. Penalties will be assessed to PC_C in the event that cargo units are not delivered or are lost (see the Appendix for details).
- Speed (PC_S) – a score from 0.5 to 1 will be assessed in Rounds 2 and 4 based on locomotive speed. This score will only apply for trains that complete round objectives; trains that do not complete round objectives will automatically receive a score of 0.5. The score will sinusoidally increase from 0.5 for a speed of 0 to 1 for the maximum speed in the class. In Round 2, the speed will be based on the average speed from the start line to the finish line. In Round 4, the speed will be based on the instantaneous speed computed at the checkpoint at the top of the hill.

- Time delay (PC_T) – a score from 0 to 1 based on any time delay greater than a specified set up time to release the locomotive. This applies to all five competition rounds. In Rounds 1 to 4 the set up time to launch will be 2 minutes; in Round 5 (division bonus round), the set up time to launch time will be 4 minutes.

The final performance criteria score is the product of all the performance criteria applicable to a given round:

Round 1: $PC_1 = PC_D \times PC_T$

Round 2: $PC_2 = PC_D \times PC_S \times PC_T$

Round 3: $PC_3 = PC_D \times PC_C \times PC_T$

Round 4: $PC_4 = PC_D \times PC_C \times PC_S \times PC_T$

Round 5: $PC_5 = PC_T$

Locomotive Criteria Scores (LC)

In addition to the performance criteria scores, the base score in each round is also modified by the spacecraft criteria scores below. These scores apply in Rounds 1 to 4.

- Cost (LC_C) – a score from 0 to 0.5 based on the total standard cost of materials and components used in the locomotive
- Energy (LC_E) – a score from 0 to 0.5 based on the number of AA NiMH batteries used to power the locomotive. A score of 0.5 will be awarded to the team that uses the least number of batteries and this will decrease to 0 for the team that uses the most.
- Aesthetics (LC_A) – a score bonus based on votes cast by the other teams in the class and the general public. During the competition, each team and guests will view the locomotives and cast four votes based on their opinion of the most aesthetically appealing. The ten teams in the class that receive the highest vote totals will get an aesthetics multiplier greater than unity, (1.20 for top team, 1.18 for second, and so on to 1.02 for tenth). Other teams will get a multiplier of unity.

The total locomotive criteria score will range from 0 to 1.20; it is the sum of the cost and energy, multiplied by aesthetics:

$$LC = (LC_C + LC_E) \times LC_A$$

Round Score

The score for Rounds 1 to 4 will be the product of the three score elements above (base score, performance criteria score, and locomotive criteria score):

$$S = B \cdot PC \cdot LC$$

For Round 5, the score will be a bonus based on relative ranking to the other divisions. Locomotive criteria scores will not factor into the Round 5 score. The Round 5 bonus score will be 5 points for the top-ranked division in this round, 3 points for second-ranked, 1 point for third-ranked, and 0 points for last-ranked.

Final Score

The final score for each team will be determined by weighting that team's best scores from the four rounds, with the fifth round division score acting as a bonus:

$$\textit{Final Score} = 30\% \times S_1 + 27\% \times S_2 + 23\% \times S_3 + 20\% \times S_4 + \textit{Round 5 Bonus}$$

where S_i is the i^{th} highest score from the first four rounds.

4.6 Competition Restrictions

Restrictions will be imposed during the project to ensure that the competition is fair and safe for all. A partial list of restrictions is included below. Violation of any restrictions may result in a grade penalty or disqualification (with a competition grade of 0). Project organizers hold the right to add, remove, or modify restrictions as they see fit to ensure fairness and safety in the competition.

- **Size restrictions**: locomotive and train dimensions are restricted in three ways: there will be at least 6″ of overhead clearance (measured from the top of the rail); there will be at least 3″ of lateral clearance (measured from the outside of the rails); the train (locomotive with freight cars) must fit in the 36″ space behind the starting gate. Note that the vertical and lateral clearances apply to the locomotive as well as the freight cars loaded with cargo. Also note that the lateral clearance measurement also applies on curved sections—the middle of a long locomotive will extend further off the side of the track than the ends of the locomotive. The overall locomotive dimensions shall remain constant through the competition; for example, it is not permissible to extend the front of the locomotive in Round 1 to gain an advantage in the hill climb.
- **Integrity**: All locomotive components shall remain on the locomotive at all times; it is not permissible to have any components left behind, launched, or dropped. Likewise, a tethered item (such as connected to the locomotive by a string or wire, for example) is not sufficient for a component to be considered "on" the locomotive (e.g. ejecting a component from a locomotive or separating a locomotive into multiple parts is not permitted, regardless of whether or not the various elements are tethered or connected).
- **Autonomous operation:** the locomotive must operate autonomously once released. There can be no interaction with the locomotive through any means (including RF or other remote control, or any form of physical connection) while the devices are in operation after release.
- **Contact with the track and playfield**: the locomotive shall contact only the rails of the track in the same fashion as a standard railway. Traction and stabilising forces created through clamping or otherwise affixing the locomotive to the track or rails in any fashion is not permitted. Contact with any part of the playing surface other than the metal rails (i.e. the track ties, competition playfield surface, structures or other surfaces) is prohibited. In the event of a derailment, a scoring penalty is applied. With an accidental derailment, at the discretion of the instructions, train progress beyond the point of derailment may be counted.

- **Railcars:** All teams shall use the supplied railcars, and may not modify or damage them in any way. Each team will need to decide how many rail cars will be attached during competition rounds. Details of the railcars and connection requirements to the locomotive will be announced in class.
- **Cargo:** Cargo will consist of square cross-section steel bars. Only the supplied cargo shall be used, and it shall not be modified or damaged. Cargo shall be placed in the railcars using the containment provided. No additional constraints such as magnets, glue, tape, straps, covers, shims, and spacers shall be permitted.
- **Round duration**: unless otherwise noted, each round is limited to a maximum duration of two minutes from the time of the start signal, with Round 5 limited to four minutes.
- **Aesthetic elements**: in trying to revitalize the public perception of railway transportation, the locomotive may include elements that serve the purpose of enhancing the aesthetic appeal. Such elements shall be considered part of the locomotive and shall remain on the locomotive during all phases of the competition, including all five competition rounds. If an aesthetic feature is removed, the locomotive may be disqualified from consideration of the aesthetic bonus, at the discretion of the course instructors. Aesthetic elements shall also be included when determining locomotive cost.
- **Light gate triggering**: photo-electric timing gates using infra-red and laser light beams will be used. Unless otherwise noted, the height of the beam will be between 0.5″ and 2.5″ from the track surface. For this entire height range, locomotives shall be designed in such a way as to continuously interrupt the beam for at least 100 milliseconds. A locomotive is considered to have crossed a gate or checkpoint as soon as a timing gate is triggered; it is not necessary for the entire locomotive to cross the gate.
- **Locomotive modifications**: locomotive repairs and minor modifications are permitted between rounds. Teams may choose to tune their design for different rounds (e.g. reprogramming a microcontroller or changing gears). For the purpose of determining locomotive system cost, all materials must be included and all components must be carried on the locomotive at all times. In the event of a repair, components can be replaced with identical components for no penalty to cost. For repair modifications involving significant changes to the locomotive, speak to one of the instructors during the competition for a ruling on any impacts to scoring (e.g. it may be necessary to re-cost your locomotive).
- **Test runs**: no test runs on the competition playfield will be permitted prior to or during the competition.
- **Markings**: each locomotive shall have the team number clearly visible and marked in text at least 5 cm high on both sides. Each locomotive shall also have the centre of gravity marked and clearly visible on both sides using a 1″ diameter three-circle, black-and-white bullseye (i.e. ◎, available on MS Windows or MacOS as Wingdings font, character 165 (Unicode character F0A5), 110 point font). The centre of gravity shall be accurate to ±1″, demonstrable upon request during the competition.

- **Battery and chemical energy**: only commercially available NiMH AA batteries with a maximum capacity of 2400 mAh and a cell voltage of 1.2 volts DC are permitted for powering the drive system. Other electronic elements, disconnected from the drive system, may be powered with commercially available DC batteries, with outputs less than 9.5 volts. No other sources of energy are permitted (i.e. the use of pressurized gases or liquids, including air or other substances) is not permitted.
- **Standard drive motors**: teams shall use only the DC motor provided by the instructors to drive the locomotive. Teams may use multiple motors, if they choose. The motor data sheet will be posted on Connect. Each team will receive one free motor, and additional motors will be made available for purchase.
- **Released substances**: the release of any substances or components during competition is prohibited.
- **Damage to competition equipment**: damage to the track or any other equipment provided for the competition may result in a penalty. The penalty will be severe for damage resulting from a negligent or deliberate action.
- **Hazardous materials**: the incorporation of hazardous materials in the construction or operation of the locomotive is prohibited. This includes, but is not limited to, controlled substances identified as dangerous goods; flammable or volatile gasses or liquids; and solids that are normally in gaseous form under standard conditions (such as "dry ice" or solid air).
- **Safe operation**: locomotives shall be operated in a safe manner. At the discretion of the course organizers, any system deemed to be unsafe may be penalized or disqualified from the competition.
- **Budget**: the cost of goods of components for the locomotive is limited to $400 (in accordance with Section 5.3). Items and supplies used in development but not implemented on the locomotive for competition are not included in this budget.

If teams believe they have found a loophole that they intend to exploit, we strongly recommend that they consult the instructors at the earliest opportunity for a private ruling on the acceptability of their intended approach to avoid being caught by a later rule change.

5.0 PROJECT CONSTRUCTION DETAILS

In order to successfully complete all project requirements, teams will need to produce a number of deliverables including not only the competition locomotive but also focused physical prototypes, reports, presentations, and so on. The deliverables, materials available for use in their production, and budgeting details are described in the sections below.

5.1 Deliverables

The items that you will prepare as part of your MECH 223 project are outlined in Table 1 below.

Table 1 - Project Deliverables

Deliverable	Description and Additional Information	Deadline (s)
Project Management Charts	Each team shall prepare and submit a CPM/PERT chart and Gantt on Jan 8. In addition, updated Gantt charts shall be submitted at the start of Weeks 3 and 4. Further instructions will be given in class.	Mon, Jan 8, 9:00 am Mon, Jan 15, 9:00 am
Logbook and Project Binder	Each team shall maintain a physical logbook and project binder which together contain all relevant project development information. These items must be brought to each design meeting to be checked by the TA and they will be graded at the end of the project. Guidelines for logbooks and the project binder are available on the MECH 223 page of Connect.	Shall be brought to every design meeting; submitted Mon, Jan 29, 9:00 am. In addition, the logbook shall be brought to every tutorial.
Prototype	Each team shall fabricate and demonstrate a physical prototype which is used to inform design decisions for the project. Additional information can be found the MECH 223 page of Connect.	Weeks 2 and 3 during the “Prototype Demo” (refer to timetables)
Poster Presentation	Each team shall prepare a poster presentation, for a public audience, outlining the development of their device. Additional information will be provided in class.	Wed, Jan 24
Competition Locomotive	Each team shall prepare a device for use in the competition.	Wed, Jan 24
Oral Presentation	Each team shall prepare a 12-minute formal technical presentation outlining the development of their device. Additional information will be provided in class and through MECH 226.	Fri, Jan 26
Final Report	Each team shall prepare a formal recommendation report outlining the development of their device, conclusions, and recommendations to the client. Guidelines will be provided in class and through MECH 226.	Mon, Jan 29, 9:00 am

5.2 Materials

Teams will be supplied with one DC motor free of charge. NiMH batteries and charger will be loaned to each team.

An on-line ordering form link will be posted on Connect for teams to purchase special MECH 223 items internally from the department. These orders will be filled and be made available for pick-up at a designated time. Details on payment and availability will be announced in class.

Shop materials and waterjet use will also be available at the regular shop rates. Waterjet use is charged at $1 per minute cutting time. Aluminum is $22/kg, steel is $9/kg, stainless steel, brass, copper and plastics such as Delrin and polycarbonate are $24/kg. All charges shall be recorded using the Machine Shop's reporting form (Material and Water-jet Use Tracker form; link is on the site http://technicalservices.mech.ubc.ca/machine-shop/ for both the form and the spreadsheet of recorded data). Note that costs reported in the Bill of Materials (see section 5.3) for stock material purchased from the machine shop shall be at shop rates.

Teams shall use the following in the Speed Chart code field on the Shop's Water Jet and Material Use Reporting Form HBDR-XX where the XX is replaced by the team number.

Teams will be expected to settle accounts at the end of the course paying for any outstanding charges for materials, water-jet use and for items from the toolkits that are missing or broken. All team members share equally in the costs. Outstanding charges will be passed on to the university's administration and the university administration may add additional charges to outstanding late payments as well as apply other penalties.

There will be restrictions on materials and components that can be used in constructing the devices for the competition. Teams are responsible to procure and/or purchase their own items. Allowable items are divided into three main categories:

- **Stock materials**: stock construction materials such as sheet, bar, plate, tube, wire and other structural forms made from materials that do not violate the restrictions in 3.5 may be used A pricelist with some common stock materials, including some non-standard items such as wheels, will be distributed early in the project.
- **Off-the-shelf components**: standard parts found in catalogues (see Section 5.3) including items such as gears, pinion shafts, bearings, pulleys, couplers, clutches, lead screws, sprockets, belts, precision shafting, and wheels; fasteners, clamps, spacers, standoffs and pins; springs; o-rings and seals; resistors, capacitors, breadboards, prototype boards, solenoids, integrated circuits (ICs), LEDs, and batteries. Each "off-the-shelf" item used must be referenced to a specific part number in one of the approved catalogues in Section 5.4; the catalogue price **in Canadian dollars** (complete currency conversion if necessary) will be used in budget calculations. If a comparable part cannot be found in a catalogue, a request to have a part allowed as a "special item" can be made.
- **Special Items**: teams are encouraged to only use items in the above two categories but may request to use special items. The **request must be made in writing to Mr. Fengler – allow a minimum of 48 hours** for evaluation. Most special items will carry a budgetary penalty reflecting the additional engineering which went into producing the items. All special item approvals must be included with your Bill of Materials when submitted (see section 5.3).

5.3 Bill of Materials

Each item used in the competition locomotive must be accounted for in a detailed bill of materials (BoM) that shall be included in the project report. **All prices must be in an "as new" value in**

Canadian dollars. (Note that shipping charges and taxes are not included in BoM costs.) The spirit of the competition is to develop a locomotive with competitive performance at competitive cost based on the regular cost of components. The budgeting system used is intended to be fair for all teams regardless of materials they might have access to at home or retailers they may or may not be aware of.

A pricelist for stock materials and common components will be distributed on Connect. Off-the-shelf components must be referenced to one of the following approved parts catalogues:

- McMaster-Carr (www.mcmaster.com)
- W.M. Berg (www.wmberg.com)
- Misumi (us.misumi-ec.com)
- Pololu (www.pololu.com)
- Nordex (www.nordex.com)
- DigiKey (www.digikey.ca)
- Electrosonic (www.e-sonic.com)
- Stock Drive Products / Sterling Instrument (www.sdp-si.com/)
- Lee's Electronics (leeselectronic.com)

Pricing from any other sites (e.g. discount sites such as Amazon, Aliexpress, Banggood) is not valid. The project BoM will require a detailed description of each part, the catalogue referenced, the part number in the catalogue, and the price. For example, see Table 2 below.

Table 2 - Sample Bill of Materials Entries

Part	Part No.	Supplier and website	Qty.	Unit Price	Currency	Unit Price (CAD)	Price (CAD)
#10-32 x 1" stainless steel socket head cap screw	DKS-A6-11	Nordex Design Guide #104 (https://catalog.nordex.com/p5212)	5	$0.35	USD [1:1.4 exchange rate]	$0.49	$2.45
Chassis frame (¼" x ½" flat bar, aluminum 6061)	8975K591	McMaster Carr (https://www.mcmaster.com/#standard-aluminum-sheets/=15ptvew)	0.75ft	$1.15 /ft	USD	$1.61/ ft	$1.21
Wheel (2" plastic on axle)	N/A	MECH 223 Price Guidelines (Connect)	4	$4.00	CAD	$4.00	$16.00
...	...	...	...	...			...

In cases where pricing depends on quantity (such as with a discount for purchase of large quantities), the quantity used in the final design as submitted will determine unit pricing. In cases where the same part is available in multiple catalogues, teams are free to choose which catalogue to reference. The cost to be used in the BoM for "special items" (from Section 5.2) will be determined by Mr. Fengler. For special items, there will be a cost penalty that includes approximate engineering and administrative costs.

As part of the competition score is based on the final cost of your design, all BoMs will be posted for review by other teams during the competition. Any challenges to your BoM that are reviewed and upheld by instructors will result in a penalty equal to the amount of cost difference. In other words, if you claim a total cost of $100 but another team is able to convincingly show this amount should have been $125, your actual cost used for scoring will be adjusted to $150. BoMs will not go down due to errors.

5.4 Student Shop Access, Toolkits, and Other Details

All students registered in MECH 223 are eligible to use the Student Machine Shop for access to the water-jet cutter and other machinery during Student Shop hours. An on-line booking system is in place for booking shop space and for reserving some of the more popular equipment. Every user must book space to be permitted into the shop (first-time users need to create a booking account). Consult the Student Machine Shop website for details:

http://technicalservices.mech.ubc.ca/machine-shop/student-machine-shop/

Each team will be eligible to borrow a toolkit for the duration of the course. These kits will be available for pick-up in the afternoon of January 5th. Students will need to ensure they have secure storage for their kits (the kits will fit in the Mech 2 lockers, and each team will be assigned a locker). A list of the contents and the part number, supplier and replacement cost of each item will be posted on Connect.

Students will have 24 hr access to FDM style 3D printers set up for printing 1.75mm PLA filament (MonoPrice Mini 3D Printers). Students will need to download the software from the Student Shop website. These printers will be set up in Kaiser 1180. It is suggested that students use a sign-up sheet and a first-come/first served system for each printer to help ensure fair access. Students are strongly encouraged to handle the printers carefully as there is no guarantee that we can repair or replace damaged equipment.

PLA filament for the 3D printers will be made available for purchase with the materials kit. Teams are free to source and obtain their own PLA filament. The printers are not to be used for ABS filament.

Two miniature lathes (Sherline) will be set up in K1180 to allow production of precision small parts.

A variety of parts and materials will be made available for purchase via an online ordering system that will be handled by a TA. This is intended to provide access to a basic set of components only and you are encouraged to also look elsewhere for components and materials. The primary responsibility of procuring parts and materials for the projects rests with the teams.

Teams are encouraged to seek inexpensive sources of materials where possible (such as surplus, refurbished, and scrap components). Mass-produced consumer items (such as toys and old computer printers) are good sources for inexpensive components including shafts, gears, wheels, and pulleys. On all parts, new or used, the value used for determining the project budget will be based on the “as-new” cost in accordance with Section 5.3.

Many suppliers do not process and ship orders quickly enough to be suitable sources of components for such a short duration project unless you use expedited shipping and brokerage services. (McMaster-Carr, Amazon and DigiKey are notable exceptions that offer two-day shipping in many instances.) If you are ordering any components, be sure to inquire about delivery time and costs with the supplier; likewise, be sure to confirm that delivery to Canada is possible in an acceptable time and for a cost that you are willing to pay. Some courier companies will add charges for brokerage and import fees, tariffs and duties and clearing items across the Canada-US border an add several days of delay to the delivery of your order.

Note: McMaster-Carr will not ship to private addresses in Canada; however, they will ship to UBC Vancouver Campus, allowing you to make purchases on your personal credit card. Shipping times are 1-2 days. For small boxes (30cm x 20cm x 20cm; 1 kg) the shipping cost is about $20. Consider combining orders with others to save on shipping.

Important: ECE is handling receiving and purchasing for the MECH department. Email purchasing@ece.ubc.ca with the subject line "Expecting Shipment from…" to generate an automated Request Ticket (RT) six-digit number. Include your name, team number, and student number in this email, along with "MECH 223". You should see an automated reply in your inbox a few minutes after sending the request. Use this RT number in the address for your shipment. Please address your shipments as indicated below to avoid delays and lost shipments:

> UBC Electrical and Computer Engineering
> Attn: Your Name, MECH
> RT + 6-digit number
> 112B - 2356 Main Mall
> Vancouver BC V6T 1Z4
> Canada

Items may be retrieved from ECE Receiving in MCLD 112B during their operation hours.

Some local suppliers for basic components and materials include the following:

- Art Knapp Trains (4391 King George Blvd., Surrey)
- Canadian Tire (2290 Cambie Street, Vancouver)
- Central Hobbies (2825 Grandview Hwy, Vancouver)
- COE Lumber and Building Supply (3485 W Broadway, Vancouver)
- Dunbar Lumber (3637 W 16th Avenue, Vancouver)
- The Home Depot (900 Terminal Avenue, Vancouver)
- Home Hardware (4459 W 10th Avenue, Vancouver)
- Industrial Plastics and Paints (150-12571 Bridgeport Rd., Richmond)
- Lee Valley Tools (1180 SE Marine Drive, Vancouver)
- Lordco Auto Parts (338 E 2nd Avenue, Vancouver)
- Magic Box Hobbies (2105 W 37th Avenue, Vancouver)
- Metal Supermarkets (7755 Venture St., Burnaby and 14271 Knox Way, Unit 140, Richmond)
- Princess Auto (15 King Edward St, Coquitlam)
- RP Electronics (4181 Dawson Street, Burnaby) easily reached via transit

6.0 CONCLUSION

The first MECH 223 project focuses on the design, construction, and operation of a cargo-hauling locomotive. Each team will develop their own locomotive for a class-wide competition testing the speed, cargo hauling and safe track negotiation on a complex track mounted on a level or inclined playfield. The locomotives will be scored based on performance (i.e. how well they complete the assigned tasks) as well as the criteria based ona system cost, energy use, and aesthetics.

A small portion of the course grade will be assigned to the competition score. A larger contribution to the grade will come from presentations of the design process used to develop the spacecraft. The presentations will include:

- A poster display for a public audience immediately prior to the design competition on Wednesday, January 24
- A technically focused oral presentation to a mixed audience on the Friday following the competition (January 26)
- A formal technical recommendation report with specific recommendations for the client submitted on Monday, January 29

Additional project information will be provided on Connect and distributed in class.

APPENDIX – COMPETITION SCORING DETAILS

The final score for each team is determined by weighting that team's best scores from the four rounds with the fifth round division score acting as a bonus:

$$\textit{Final Score} = 30\%\times S_1 + 27\%\times S_2 + 23\%\times S_3 + 20\%\times S_4 + \textit{Round 5 Bonus}$$

where S_i is the i^{th} highest score from the first four rounds.

For Rounds 1 through 4, scoring is based on a combination of three main elements: base score (B), performance criteria score (PC), and locomotive criteria score (LC). The base score is determined from the portion of track completed in a given round. The performance criteria scores change from round to round and account for factors such as average speed, distance travelled, timely operation, and so on. The locomotive criteria scores factor into Rounds 1 and 4 only and include the considerations of locomotive cost, energy usage, and aesthetics.

The score components are used to determine a score for one round as:

$$\text{Round Score} = B \times PC \times LC \tag{A-1}$$

The base score in Rounds 1 to 4 range from 0 to 100; the Round 5 base score is shown separately below.

The final performance criteria score in Round i (PC_i) is determined according to the product of all performance criteria elements applicable to that round:

Round 1: $PC_1 = PC_D \times PC_T$

Round 2: $PC_2 = PC_D \times PC_S \times PC_T$

Round 3: $PC_3 = PC_D \times PC_C \times PC_T$ (A-2)

Round 4: $PC_4 = PC_D \times PC_C \times PC_S \times PC_T$

Round 5: $PC_5 = PC_T$

Similarly, the total locomotive criteria score is the sum of the cost and energy, multiplied by aesthetics:

Rounds 1-4: $LC = (LC_C + LC_E) \times LC_A$ (A-3)

Round 5: $LC = 1$

Each of the base score, performance criteria, and locomotive criteria elements are described in detail below.

The organizers reserve the right to change any of these parameters. As much advance notice as possible will be given (where applicable). Some reasons for change include unavoidable restrictions in the track design or competition area and adjustment to ensure that all teams have a reasonable chance of success in the competition. **If teams believe they have found a loophole that they intend to exploit, we strongly recommend that they consult the instructors at the earliest opportunity for a private ruling on the acceptability of their intended approach to avoid being caught by a later rule change.**

A-1 Base Score (B_i)

With reference to Figure 7, the base score in each round is determined based on how far along the track the team progresses. For Rounds 2 to 5, progress will be measured using laser light timing gates, indicated in the figure with a line and number (i.e. ❶,❷,❸,❹, and ❺). Specifically, the base score for Round *i*, B_i, will be determined as follows:

- Round 1 (B_1): points awarded based on the maximum elevation reached by the front of the locomotive relative to the elevation reached by other teams. B_1 will start at 0 for no elevation gain and will increase linearly to 100 for the maximum elevation gain by all teams.
- Rounds 2 and 3 (B_2 and B_3): points will be awarded based on how far along Track A the locomotive is able to travel. The track will include two laser timing gates (❶ and ❷) and two visual indicator lines, not timing gates (⑥ and ⑦). For crossing each gate and indicator line, with all wheels of the train remaining on the track while crossing, the team will receive 25 points. Thus, the total base score for traveling from start gate ❶ to finish gate ❷ on the rails is 100 points.
- Round 4 (B_4): the base score in Round 4 is based on how far along Track B the locomotive is able to travel. This track will include four laser timing gates (❺,❸,❹, and ❷) and one visual indicator line (⑧). The team will receive 25 points each for crossing gates ❺,❸, and ❷, and line ⑧, with the locomotive remaining on the track while crossing. Note that gate ❹ is used to determine speed at the top of the hill and does not contribute to the base score. The total base score for travelling from the start gate ❺ to finish gate ❷ on the rails is 100 points.
- Round 5 (B_5): The base score in the Round 5 relay is based on the progress of the five locomotives from the division. For a locomotive starting on Track A, it will receive 1 point for fully crossing the start line (❶), 1 point for entering the transition region (see Figure 7), and 3 points for crossing the finish line (❺). For a locomotive starting on Track B, it will receive 1 point for fully crossing the start line (❺), 1 point for entering the transition region, and 3 points for crossing the finish line (❶).

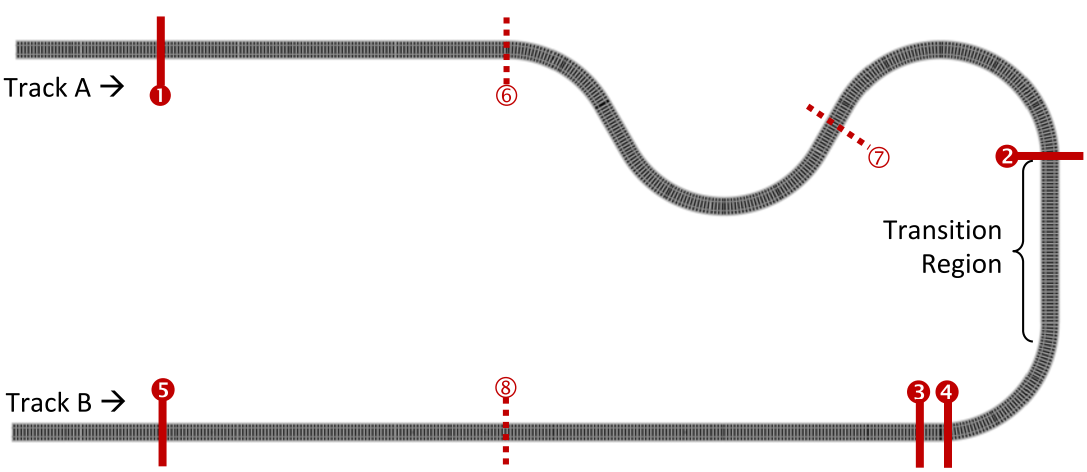


Figure 7. Base Score Checkpoints and Gates

The base score will be multiplied by a series of evaluation criteria; these consist of performance criteria (PC) and locomotive criteria (LC), as described below.

A-2 Aesthetics Score (LC_A)

The aesthetics score is a small bonus based on votes cast by the class and the general public. During the competition, each team will view the locomotives of other divisions and cast votes based on their opinion of the best, second best, third best, and fourth best devices from other divisions. (Teams may not vote for locomotive within their own division.) Members of the general public will also be able to cast a single vote for their opinion of the best device from the class. The ten teams in the class that receive the highest vote totals earn the following bonuses in Rounds 1 to 4:

- LC_A = 1.20 for top team
- LC_A = 1.18 for second team
- . . . (A-4)
- LC_A = 1.02 for tenth team
- LC_A = 1.00 for other teams

For Round 5, LC_A = 1 for all teams.

A team must submit their voting ballot before the end of the competition in order to be eligible for the aesthetics bonus.

A-3 Locomotive Cost Criterion Score (LC_C)

The cost score is based on the total catalogue cost (*C*) of all components and materials used in the locomotive. If multiple system configurations are used for the different rounds (such as by changing wheels, gears, or other components), *C* will be based on the total cost of all configurations for ***all*** rounds.

The actual cost spent by teams should be substantially less as teams will be encouraged to use surplus, scrap, and salvaged parts where possible. A maximum (catalogue) budget of $400 has been specified. The locomotive cost score takes the form as shown in Figure 8 and equation below.

$$LC_C = \begin{cases} 0.5 & \$0 \le C \le \$50 \\ 0.25 + 0.25\cos\left(\dfrac{C - \$50}{\$350}\pi\right) & \$50 < C < \$400 \\ 0.0 & C \ge \$400 \end{cases} \tag{A-5}$$

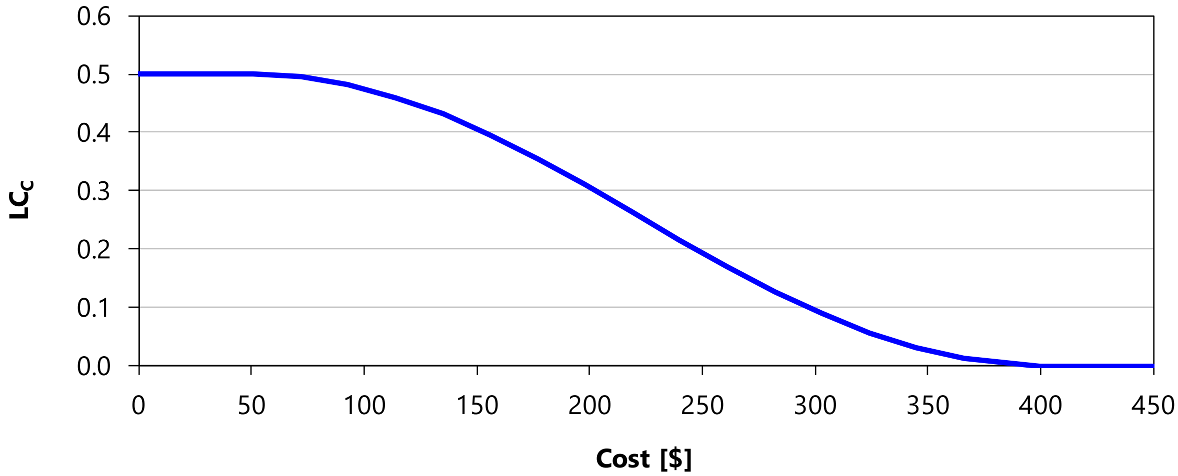


Figure 8. Cost Criterion Score

A-4 Locomotive Energy Criterion Score (LC_E)

The energy score is based on the maximum number of AA NiMH batteries that are used to power the drive system of the locomotive in all rounds. Teams are allowed to modify the number of batteries actively powering the drive motors for different rounds by electrically disconnecting batteries, but they must keep all batteries onboard their locomotive for all rounds. Teams may substitute fresh batteries for partially discharged batteries between rounds without having to carry both sets of batteries on board.

The locomotive energy score takes the form as shown in the equation below, where n is the number of AA NiMH batteries used, n_{min} is the minimum number of batteries used by all teams, and n_{max} is the maximum number of batteries used by all teams.

$$LC_E = 0.25 + 0.25\cos\left(\frac{n - n_{\min}}{n_{\max} - n_{\min}}\pi\right) \tag{A-6}$$

In the event that $n_{max} \leq 3 \cdot n_{min}$, a value of n_{max} of $3 \cdot n_{min}$ will be used for n_{max}.

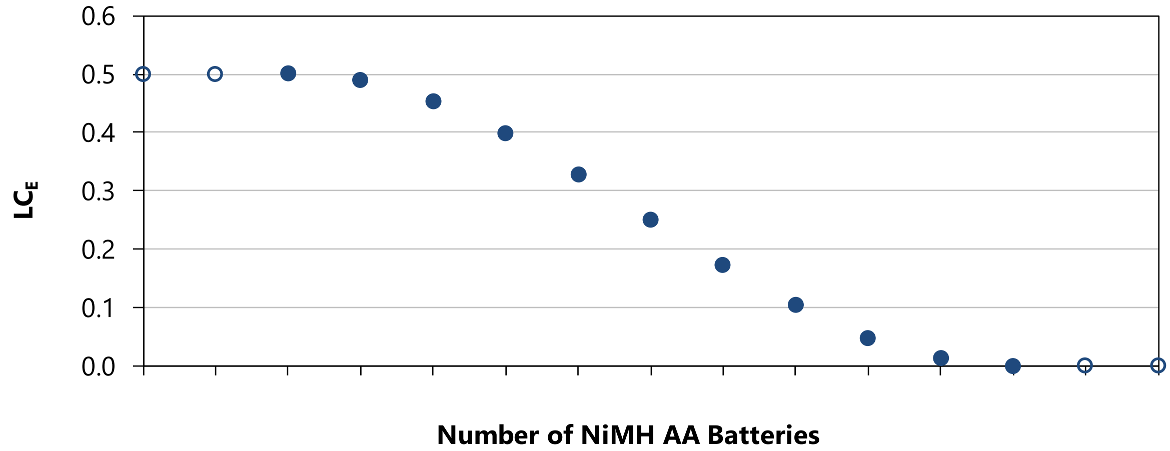


Figure 9. Energy Criterion Score

A-5 Cargo Transport Rate Criterion (PC_C)

The cargo transport rate criterion (PC_C) applies to Rounds 3 and 4, and is based on the rate of cargo transport ($\dot{n}$, units/second) for teams to travel a designated track segment (see below). The score will sinusoidally increase from 0.5 for no cargo transported to 1 for maximum cargo transport rate, as shown in the equation below.

$$PC_C = 0.75 - 0.25\cos\left(\frac{\dot{n}_{\max} - \dot{n}}{\dot{n}_{\max}}\pi\right) \tag{A-7}$$

where $\dot{n}$ is the team's cargo transport rate, and $\dot{n}_{\max}$ is the maximum cargo transport rate of all successful teams in a round. This relationship is shown graphically in Figure 10 below.

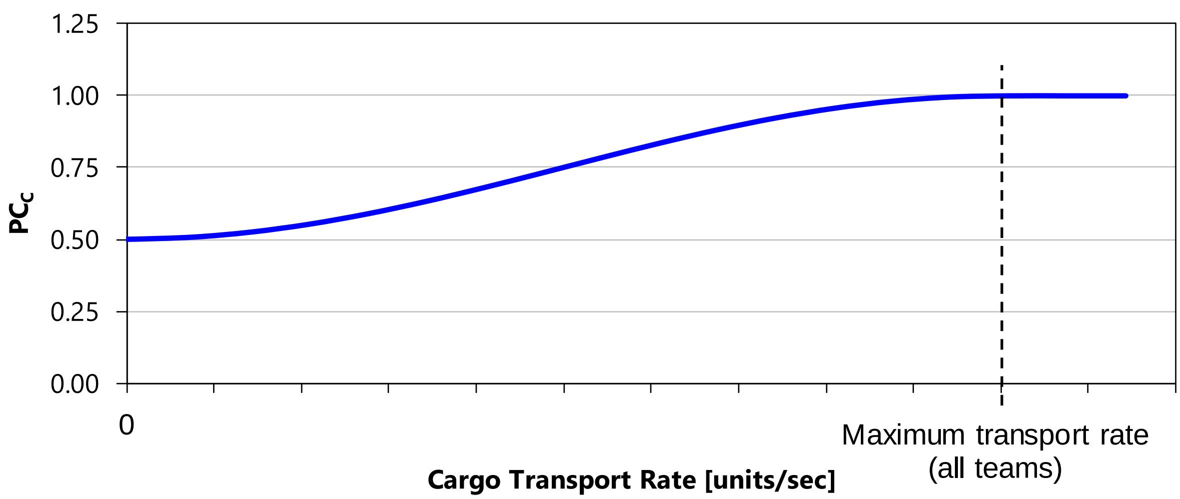


Figure 10. Cargo Transport Rate Performance Criterion Score

Trains that do not complete round objectives will automatically receive a score of 0.5. In Round 3, the cargo transport rate will be determined between the start line and finish line. In Round 4, the average speed will be determined between the checkpoint at the top of the hill and the finish line at the bottom of the hill (see Figure 5). Penalties will be assessed to PC_C in the event that cargo units are not delivered:

- If a rail car separates from the locomotive, but remains on the track, and cargo is not carried to the finish line, a penalty equal to the number of cargo units left behind will be assessed when determining PC_C, with a minimum of zero total scored units. For example, if a team starts with 10 cargo units and 3 are not carried to the finish but remain in the rail car and the rail car remains on the tracks, the team will be scored for 4 cargo units (i.e. 7 successfully delivered – 3 not delivered). If a team starts with 10 cargo units and 6 are not carried to the finish, the team will be scored for zero cargo units (not 4 – 6 = -2 units).
- If a rail car derails, or if cargo blocks are spilled or lost during the round, a penalty equal to two times the number of blocks lost will be assessed, with a minimum of zero total scored units. For example, if a team starts with 10 cargo units and 3 are spilled from the rail car during the round, the team will be scored for 1 cargo unit (i.e. 7 successfully delivered – 2×3 spilled).

A-6 Derailment Performance Criterion (PC_D)

The derailment performance criterion (PC_D) will take the value of 0.5 of 1.0 for Rounds 1 to 4. If the locomotive and all rail cars hauled by the locomotive properly remain on the tracks, PC_D will take the value 1.0 for that round. If the locomotive, or any rail cars hauled by the locomotive, derail (i.e. permanently leave the rails), PC_D will take the value of 0.5. It is not necessary for any part of the train to contact the playfield surface to qualify as a derailment. For Rounds 1, 2, and 3, the train must not derail for the track segment from the start line to finish line. For Round 4, the train must not derail, from the start line to the finish line and beyond through the runout section (see Figure 5).

A-7 Speed Performance Criterion (PC_S)

The speed performance criterion (PC_S) is used in Rounds 2 and 4, and it measures the speed at which the locomotive traverses a designated track segment. Trains that do not complete round objectives will automatically receive a score of 0.5. The score will sinusoidally increase from 0.5 for a speed of 0 to a maximum score of 1 for the fastest speed in the class. In Round 2, the speed will be based on the average speed from the start line to the finish line, and to successfully complete the round, the team must traverse this distance without derailing and within 2 minutes. In Round 4, the speed will be based on the instantaneous speed computed at the checkpoint at the top of the hill (see Figure 5). To successfully complete Round 4, the team must pass the checkpoint and finish line, and must not derail at any point on the track, as defined in Section A-6.

The function describing PC_S is given by:

$$PC_S = 0.75 - 0.25\cos\left(\frac{v_{\max} - v}{v_{\max}}\pi\right) \tag{A-8}$$

where v is the measured speed and v_{max} is the maximum speed from all teams that successfully complete the round objectives. This relationship is shown graphically in Figure 11 below.

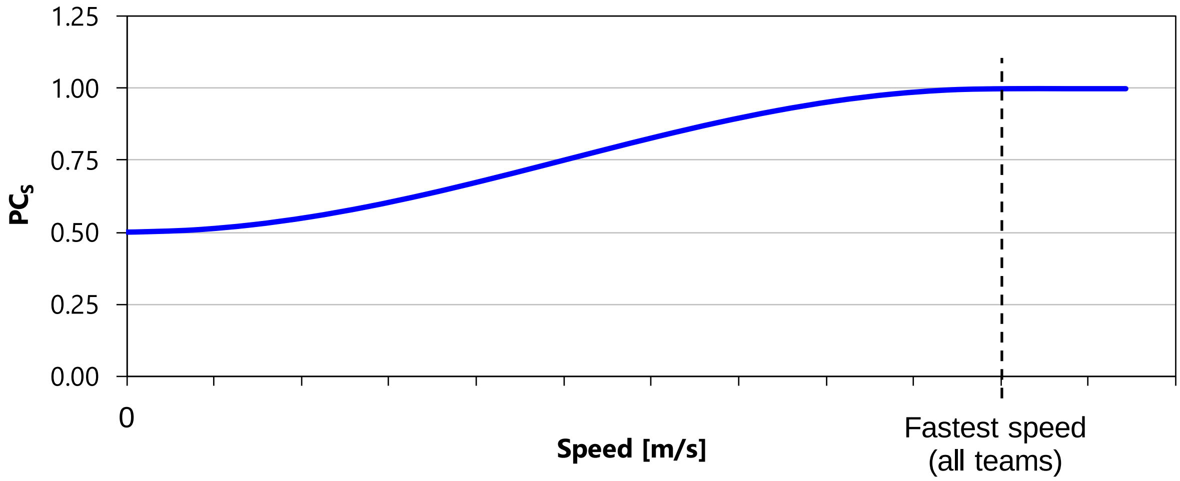


Figure 11. Speed Performance Criterion Score

A-8 Time Delay Penalty Performance Criterion (PC_T)

Teams will have 2 minutes to release their locomotive from the time they are called to compete (4 minutes for Round 5). After this time, a release time delay penalty will be applied; the penalty will start at 0% and will grow linearly to a maximum of 100% after an additional two minutes. The penalty is phrased in terms of a score multiplier as given below:

Rounds 1-4:

$$PC_T = \begin{cases} 1 & t_{release} \le 120 \text{ sec} \\ \dfrac{240 - t_{release}}{120} & 120 \text{ sec} < t_{release} < 240 \text{ sec} \\ 0 & 240 \text{ sec} < t_{release} \end{cases} \tag{A-5}$$

Round 5:

$$PC_T = \begin{cases} 1 & t_{release} \le 240 \text{ sec} \\ \dfrac{360 - t_{release}}{120} & 240 \text{ sec} < t_{release} < 360 \text{ sec} \\ 0 & 360 \text{ sec} < t_{release} \end{cases} \tag{A-6}$$

where $t_{release}$ is the time to release, in seconds, from when the team is first called. Teams will not be penalized for delays enforced by the organizers (e.g. if a team is ready to release their spacecraft, but they are forced by the organizers to wait while the playfield is reset in some way, the team will not be penalized).

A-9 A Closing Note on Requirements and Evaluation Criteria

In reviewing the rules and scoring system above, you should have in the back of your mind what these things mean in the context of MECH 223. Specifically, you should be able to relate these elements to design requirements and evaluation criteria. The restrictions in Section 4.6 all translate into ***requirements***, but these are not the only requirements. For example, there is also an implied requirement that the locomotive is ready to compete on January 24th (i.e. the latest date that the locomotive must be ready to compete to gain any points in the competition is January 24th). The performance criteria and locomotive criteria above are both forms of ***evaluation criteria*** as they are a measure of the ***value*** of a design in terms of competition points. Requirements and evaluation criteria will be a focal point in the second half of MECH 223.