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Rail Hauler Simulation, Optimization, & Modeling

Note: All mentioned simulations in this document are provided in our Simulations folder (See Simulations).

Full Lap Simulation

Our full lap simulation helped us estimate how our designs would function around the track. This simulation will provide us with the estimated time for us to complete the course, as well as the velocity and acceleration throughout the track. This will help us estimate where our design is likely to fail or have issues and how each configuration will perform. Most importantly, this design will be used for velocity prediction. The simulation considers the following forces:

- Rolling Resistance
- Gravity
- Torque (Thrust)

(Other factors such as internal resistance and rotational inertia were determined to be negligible. Some factors we took precautions against to reduce the effects (Ex: Oiling Internal Machinery))

The simulation completes a force balance for each point on the example track and estimates the acceleration, velocity, and next position of the rail hauler.

Constants used in the simulation were experimentally determined:

The Rolling Resistance Coefficient C_{rr} for both the rail hauler and freight car were determined by using the distance (d) for the car running at a set velocity (v_0) to stop:

Kinematic Equation:

$$(v_f)^2 - (v_0)^2 = 2da$$

$$\frac{0-(v_0)^2}{2d} = \frac{\Sigma F}{m} = \frac{F_{rr}}{m}$$

$$\frac{(v_0)^2}{2dg} = C_d$$

This test was conducted individually for the rail hauler and freight car:

$C_{rr} = 2$ (Rail Hauler with adhesive wheels)

$C_{rr} = 0.005$ (Freight Car with metal wheels)

*Note that the rolling resistance coefficient of the freight cars are negligible in comparison to other factors.

For calculation simplicity the simulation assumes that we will not slip downwards on the hill and will maintain a speed below the rpm of the wheels. We have applied heavy strength gorilla tape which should keep us steady even on the maximum 21.8 degree downhill.

Gear Ratio Study & Score Modeling

The Score Optimization simulation allowed us to implement the provided equations in the Project 2 Guidelines Document to effectively weigh our cargo-carrying ability against our speed by choosing a specific, optimal gear ratio to maximize our score. Note that one of the benefits of us choosing the worm gear single-gear reduction drivetrain is reflected here; by slightly changing the driving gear's size, we can easily change our gear ratio. The simulation models the vehicle's performance through the "most difficult" track configuration, including minimum radius and maximum height features as highlighted in the guidelines. We also assumed two motors providing torque and a rolling resistance coefficient of 2 (found from previous project testing) to account for frictional losses. The simulation calculates lap times for two segments (Start to Mid Gate and Mid Gate to Finish) and computing their scores based on competition guidelines. These scores are iterated through gear ratios from 0 to 150 and load masses from 0 to 10 kg and displaying which combination of gears and load masses would give us the best score.

The results revealed an optimal gear ratio of approximately 55:1, hauling a load of 1.43 kilograms. This gear ratio balances the trade-off between speed. Assumptions include:

- Consistent motor performance with the specification sheet and that all mass is located at the centroid

- Sensitivity to track variations (e.g., slope length, hill placement) was not fully modeled due to the secret track configuration

Using the most demanding track variation (containing the most "difficult" track features) provides us with confidence that this simulation accurately captures the nature of the competition. Furthermore, we will continue to iterate on this simulation, choosing variable gear ratios close to 55:1 to see how much cargo our vehicle can truly carry, performing physical optimization as validation (See our Prototyping Log at A1 - Prototyping Notes Log.docx).

Derailment Calculations

This simulation (see Single_Derailment_Calculations.m and Cargo_Derailment_Calculations.m) helped us estimate the maximum speed our rail hauler could travel on the curve without derailing. For the first round, due to similarity with the previous design challenge (one single car), we used a similar simulation but added the physics of potentially jumping off the track. However, for the second round we created a more advanced simulation which took into account the multiple cargo cars we have attached to the design. The physics analysis we used for this can be found in the Basic Physics Analysis document.

The results from the Single Derailment Calculations script showed that the maximum velocity that the vehicle can travel on its own before derailing on the curve is 19.81 cm/s, where it will derail due to track jumping. The script also tests for centrifugal tipping and found that the velocity required to cause centrifugal tipping is 349.52 cm/s. Since the velocity required to cause derailment by track jumping is lower than the velocity required to cause centrifugal tipping, track jumping will occur first and therefore that is the velocity that the vehicle will derail at.

The results from the Cargo Derailment Calculations script showed that the maximum velocity that the vehicle can travel while also pulling the rail cars before derailing on the curve is identical to when the vehicle is travelling on its own, 19.81 cm/s. Because of the positioning of the rail cars and the vehicle as they're traveling around the curve, the center of gravity lies at the center of the curve, which makes it very hard to tip the train and requires 366.17 cm/s. Therefore, the vehicle will still derail by track jumping first, which means that the velocity before derailing is the same as without the rail cars.

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Motor Validation & Score Modeling

This score calculator created in MATLAB (See Motor_Net_Score_Sim.m) calculates the total score obtained by a vehicle of set parameters including mass, number of motors used, sustainability category, aesthetics, average vehicle speed, predicted vehicle average speed, gates passed, fuel cost, etc. - all relating to our 7 main evaluation criteria.

For this score calculator, we used multiple simplifications to help us optimize variables against each other. These include:

a) Aesthetics score = constant.
b) Sustainability score = constant.
c) Exact prediction of average vehicle speed
d) <aximum parameters by all teams are:
    a. Maximum average vehicle speed of 1.5m/s for round 1
    b. Maximum average vehicle speed of 1.0m/s for round 2
    c. Maximum cargo pulled of 4.0kg
e) Round 1 & Round 2 always completed by any tested vehicle
f) Track-Navigation Abilities are treated as constants throughout designs

These (significant) simplifications let us yield a simulation which keeps many vehicle-based parameters constant based on our projected understanding of how any of our designs (regardless of weight or amount of motors / number of batteries) will perform – including aesthetics, sustainability, gates passed, etc.

Resultingly, we were able to directly compare our final vehicle score to (primarily) number of motors used, given assumed equations for added mass per motor as well as additional round 2 speed & additional cargo carried per motor added.

Performing this optimized simulation multiple times, we yield:

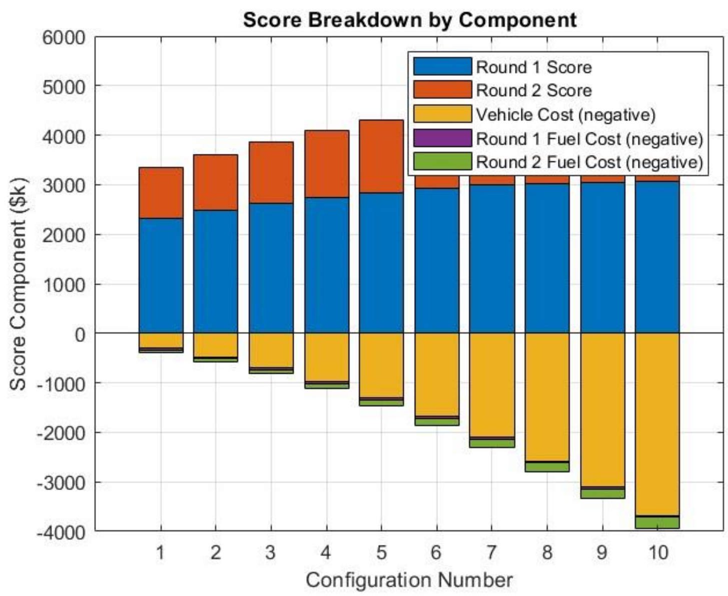

Figure A: Score Breakdown by Component per Motor Added (1-10 Motors)

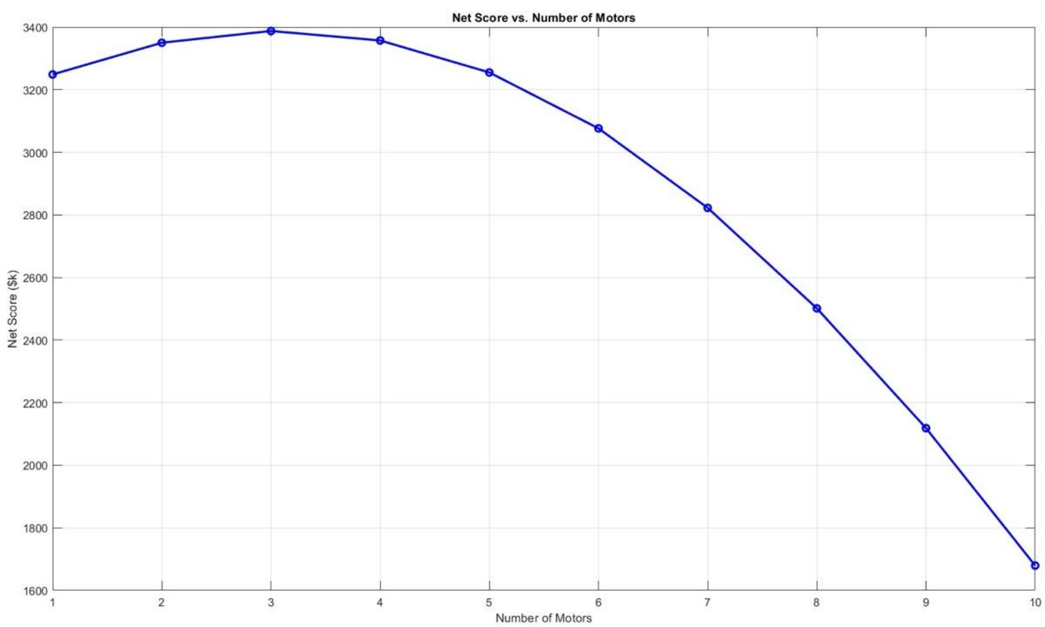

Figure B: Net Score vs. Number of Motors Used

And notice that the simulation results in a peak motor use of 3 motors total, and 2/4 motors are practically tied for 2nd. This confirms that our use of two motors is a nearoptimal value, as any additional motors would result in significant chassis changes (3+ motors equating to 6+ wheels, according to our current WDM chosen design).

We note here that this optimization is very narrow and contains many assumptions that may not hold true with additional motors added (including mainly Track Navigation ability but also factors like a decrease to accurate predicted speed values due to a higher average speed) - therefore, we believe this simulation validates our decision of a 2-motor design as we can maintain all of the navigational abilities from our vehicle during competition 1 while also incorporating a stronger design in terms of cargo-carrying ability.

Overall, this simulation mainly helps us confirm that a two-motor design is optimal but also assists us understand how we can change vehicle parameters to optimize for final score.