BioUpgrade for GE Transportation

Engineering Design 100, Section 25, Dr. Ritter

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Executive Summary/Abstract

Our goal of this project is to reduce the negative environmental impact of GE’s current transportation system while maintaining freight capacity into and out of the city of Pittsadelphia. Citizens are complaining of high levels of smog in the city, and GE is required to meet EPA Tier III standards in order to continue operation. After considering several designs, we chose to upgrade 36 of GE’s locomotives to Tier III with a NOx after-treatment, and use these to power 18 freight trains travelling to and from Cincinnatti, OH. We chose to sell the remaining Tier II locomotives and purchase 36 new Tier IV locomotives, and use these to power 12 coal trains travelling to and from Frankfort, KY. Additionally, all of these locomotives would run on B20 biodiesel fuel. We found that this solution would decrease PM and NOx emissions by 53% and 61%, respectively, increase freight capacity by 64%, increase daily profits by 88%, and have a 43 day return on investment.

Problem Statement

GE and the citizens of Pittsadelphia want all locomotives coming into and out of the city to meet the EPA Tier 3 or Tier 4 standards. Currently, citizens of Pittsadelphia are complaining of smog due to high emissions. The rest of the world is also affected by the emissions from GE’s locomotives and the transportation industry in general because they are destroying the environment. If this problem is not addressed, we will continue to destroy our planet and its inhabitants. If the problem is fixed, it will decrease the harmful effects on our environment. The problem occurs between Cincinnatti, OH and Pittsadelphia and between Frankfort, KY and Pittsadelphia where GE locomotives are carrying freight from, and must be fixed immediately in order to meet the EPA standards and protect our planet.

To address this problem we will research the current energy inputs used by GE locomotives and their effects on the environment. We will look into alternative ways to transport freight while maintaining freight capacity, delivery time, costs, and overall efficiency while reducing emissions. We will then
follow the design process to choose the best concept, prototype, test, and repeat as needed until our finished product meets all of the customer needs.

**Background**

While designing our project, we researched various solutions to ensure the practicality of our prototype. We began by researching the Environmental Protection Agency tier standards so we could ensure we met them with our design. Through our research, we found, as illustrated in Figure 1, Tier 3 standards reduce particulate matter emissions by 50%. Tier 4 standards, on the other hand, reduce PM emissions by an additional 70%, while also reducing NOx emissions by 76%, which is the cause of smog [2]. GE’s locomotives can be upgraded from Tier 2 to Tier 3 for $750,000 per locomotive, but new locomotives have to be purchased for $4 million per locomotive to meet the Tier 4 standards. The old Tier 2 trains can be sold, however, for $1.5 million per locomotive to lower the costs of the Tier 4 locomotives [2].

We researched various alternative fuels, such as biodiesel, in comparison to conventional diesel as another potential way to meet the EPA standards and reduce emissions. We found that the engine in the locomotives required an expensive upgrade to run on 100% biodiesel, but did not require it to run on 20% biodiesel [1]. B20 was a considerable alternative fuel not only because it does not require this expensive engine upgrade, but also because its energy density is 99% of the energy density of conventional diesel [1]. Additionally, B20 is only $2.92/gallon, which is cheaper than conventional diesel, priced at $3.06/gallon [2]. B20 is more environmentally efficient than conventional diesel because it lowers PM emissions by 10%, however it slightly increases the NOx emissions by 2% [1]. B20 alone is not enough to bring the Tier 2 locomotives to Tier 3 or Tier 4, but can be used in addition to other methods to reduce emissions.
Figure 1: The graph above is representing the reductions in NOx and PM emissions through the tier standards set by the Environmental Protection Agency [2].

**Customer Needs**

Before we came up with solutions to the problem, we defined our customer needs and the standards that had to be met for each need, as shown in Figure 2. Our first defined customer need was low emissions because the citizens of Pittsadelphia’s main complaint was the smog accumulating in the city. Next, we decided maintaining freight capacity and on-time delivery were also important customer needs because the purpose of the trains are solely to carry cargo from one destination to the next and decreasing these two needs would decrease revenue. To protect our main customers, the citizens of the city, we decided another important customer need was to not decrease the jobs in the city, which would displease our customers. We also found durability and long term costs important because if the locomotives do not last and the design is too expensive, GE will not want to move forward with the design. Our last customer need was not increasing the noise in residential areas because the customers would not be happy with the
new design. Finally, we compared each of these customer needs to find the relative importance of each one using the AHP matrix shown in figure 3. Through the AHP matrix, we decided that emissions and capacity were the most important, followed by long-term costs, on-time delivery, durability, and job openings.

Figure 2: The chart below defines an acceptable and idea metric for each of our defined user needs.

<table>
<thead>
<tr>
<th>Statement</th>
<th>Acceptable</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Low emissions and environmental impact</td>
<td>Tier 3 EPA standards</td>
<td>Tier 4 EPA standards</td>
</tr>
<tr>
<td>2. The solution maintains or increases freight capacity</td>
<td>165,000 tons/day</td>
<td>&gt;165,000 tons/day</td>
</tr>
<tr>
<td>3. The solution will allow on-time delivery</td>
<td>2-3 days later</td>
<td>No change in delivery time</td>
</tr>
<tr>
<td>4. The solution does not reduce the number of jobs available to residents of Pittsadelphia</td>
<td>10% decrease in jobs</td>
<td>0% decrease OR increase in jobs</td>
</tr>
<tr>
<td>5. The solution is durable and does not require much maintenance</td>
<td>20-year lifetime with $10 decrease in maintenance costs per event</td>
<td>&gt;20 year lifetime with &gt;$10 decrease in maintenance costs per event</td>
</tr>
<tr>
<td>6. No increase in long-term costs</td>
<td>2 year return on investment</td>
<td>&lt;2 year ROI</td>
</tr>
<tr>
<td>7. The solution does not increase noise in residential areas</td>
<td>90 decibels</td>
<td>&lt;90 decibels</td>
</tr>
</tbody>
</table>
Figure 3: The AHP matrix below compares each of our defined user needs against every other need to determine the relative weights of each. We found that emissions and capacity were the most important, followed by long-term costs, on-time delivery, durability, and job openings.

<table>
<thead>
<tr>
<th></th>
<th>Emissions</th>
<th>Capacity</th>
<th>Time</th>
<th>Jobs</th>
<th>Durable</th>
<th>Costs short term</th>
<th>Costs long term</th>
<th>Noise</th>
<th>Total</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions</td>
<td>1</td>
<td>1</td>
<td>3.00</td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>26.00</td>
<td>0.22</td>
</tr>
<tr>
<td>Capacity</td>
<td>1</td>
<td>1</td>
<td></td>
<td>5</td>
<td>2</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>26.00</td>
<td>0.22</td>
</tr>
<tr>
<td>Time</td>
<td>0.333333</td>
<td>0.333333</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>0.5</td>
<td>3</td>
<td>14.17</td>
<td>0.12</td>
</tr>
<tr>
<td>Jobs</td>
<td>0.2</td>
<td>0.2</td>
<td>0.333333</td>
<td>1</td>
<td>0.5</td>
<td>2</td>
<td>0.33</td>
<td>1</td>
<td>5.56</td>
<td>0.05</td>
</tr>
<tr>
<td>Durable</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>5</td>
<td>14.00</td>
<td>0.12</td>
</tr>
<tr>
<td>Costs short term</td>
<td>0.142857</td>
<td>0.142857</td>
<td>0.2</td>
<td>0.5</td>
<td>0.333333</td>
<td>1</td>
<td>0.14</td>
<td>0.5</td>
<td>2.96</td>
<td>0.03</td>
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<tr>
<td>Costs long term</td>
<td>0.5</td>
<td>0.5</td>
<td>2</td>
<td>3.05903</td>
<td>1</td>
<td>7.142857</td>
<td>1</td>
<td>7</td>
<td>22.17</td>
<td>0.19</td>
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<tr>
<td>Noise</td>
<td>0.2</td>
<td>0.2</td>
<td>0.333333</td>
<td>1</td>
<td>0.2</td>
<td>2</td>
<td>0.142857</td>
<td>1</td>
<td>5.08</td>
<td>0.04</td>
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</tbody>
</table>

Grand Total: 115.94

Concept Generation

Figures 4 (left), 5(right): Our first idea (left) was to build a biodiesel refueling station that would also function as a hub where cargo could be transferred from Tier IV trains (for travelling interstate/long distance) to Tier III trains (for travelling intrastate/short distance). Our second idea (right) was to simply use B20 biodiesel in all of our engines.
Figures 6(left), 7(right): Our third idea (left) was to upgrade all of GE’s 50 locomotives to Tier III and power them with B20 biodiesel fuel. Our fourth idea (right) was to use a combination of upgraded Tier III locomotives and new Tier IV locomotives.

To begin generating concepts, each group member brainstormed as many solutions as they could think of on their own. Next, each member shared their own designs with the group as a whole. While discussing our individual designs, we came up with more ideas as a group by coming up with new ideas and combining others. Finally, we narrowed down the all of the proposed solutions into designs we would consider and designs we would not consider, and finished with four designs we saw feasible. The four designs we considered are illustrated in figures 4, 5, 6, and 7.

**Concept Development, Cost/Benefit Analysis, Concept Selection**

To decide which ideas to move forward with, we first used the TASC (Tool for Assessing Semantic Creativity) method to rank the creativity of our ideas. Each team member anonymously chose words that they associated with each design. The computer program then assigned each word a weight and each concept a score based on the frequency and weight of each word.

Our first idea, the station, scored the highest using the TASC method. As we continued to develop this design, however, we realized that it did not have the practical merit which we had originally thought,
and we did not agree with the results. We then created a concept selection matrix to score our ideas based on our defined user needs and their weights from the AHP matrix.

Through our concept selection matrix as shown in figure 8, we found that our fourth idea, a combination of buying new and upgrading old locomotives, scored the highest, closely followed by solely upgrading, and then by biodiesel. Interestingly, our station idea scored by far the lowest using this method. We decided to move forward with a combination of biodiesel, upgrading, and buying, as each of these brought a unique and valuable aspect to the solution, and all could be used in one cohesive system.

Figure 8: The concept selection matrix below demonstrates that our last idea, a combination of upgrading and buying, had the most value based on our defined user needs.
Design Review

Through our discussions, we received feedback suggesting we look further into our return on investment so we can decide exactly how many locomotives we are upgrading to Tier 3 and how many Tier 4 locomotives we will be buying. Our feedback said our model was effective in reducing emissions and meeting the EPA requirements, but may be too expensive.

To further develop our project using this feedback, we decided to calculate the return on investment by finding the profit from the increased freight capacity, and decide on the number of locomotives that will be upgraded, sold, and bought. We will continue to search for an ideal solution in which we significantly reduce emissions while maintaining a return on investment of under two years.

Description of Final Design

We decided to upgrade 36 of the 50 current locomotives to Tier 3 and use a NOx aftertreatment system on each. These will then be used to power 18 freight trains running to and from Cincinnati, Ohio. We are going to sell the remaining 14 locomotives and use this money, supplemented by out-of-pocket funds, to purchase 36 new Tier 4 locomotives. These will then be used to power 12 coal trains running to and from Frankfort, Kentucky. Additionally, all of our engines will be running on B20 biodiesel fuel.

We found that, because each additional train brings in far more revenue per day than its initial cost divided by 730 (the amount that we would need to pay back per day to make a two year return on investment, neglecting interest), we could theoretically continue to increase our output as much as we wanted, with the only constraint being emissions. As this is dictated by both EPA regulations and public opinion, we decided to set a “cap” on emissions at 60% of the current levels, and based on this “cap” we maximized our capacity and daily profits. This led us to settle on 18 freight trains and 12 coal trains.
Our calculations explaining this are shown below:

Use Biodiesel (B20) in all engines ($2.92/gal) [1]

Upgrade 36 of the 50 Tier II engines to Tier III with after treatment.

Initial costs: $850,000 * 36 = $30.6M [2]

Sell 14 Tier II engines and buy 36 new Tier IV engines

Initial costs: ($4M * 36) - ($1.5M * 14) = $123M [2]

Use 36 Tier III locomotives to power 18 freight trains (running on B20)

Recurring costs: 7,447 gal * $2.92/gal = $21,745/train in

532 gal * $2.92/gal = $1553/train out

$23,298/train/day * 18 trains = $419,364/day [1] [3]

Use 36 Tier IV locomotives to power 12 coal trains (running on B20)

Recurring costs: 12,765 gal * $2.92/gal = $37,277/train in

1,064 gal * $2.92/gal = $3,107/train out

$40,384/train/day * 12 trains = $484,608/day [1] [3]

Total Costs: ($30.6M + $123M) + ($419,364 + $484,608)/day = $153.6M + $903,972/day

(64% increase in daily operational costs) [3]

Total Revenue: ($42/ton coal * 12,000 tons * 12) + ($20.25/ton freight * 7,000 tons * 18) =

$8,599,500/day (85% increase in daily revenue) [4]

Total Profit: $8,599,500/day - $903,972/day = $7,695,528/day (88% increase in daily profits)

Total Capacity: (18 freight trains * 7,000 tons/freight train) + (12 coal trains * 12,000 tons/freight train) = 270,000 tons (64% increase in capacity) [2]
Total PM Emissions: \((0.1 \text{ g/hp-hr} \times 0.9 \% \times 20 \text{ hr} \times 4500 \text{ hp} \times 36 \text{ locos}) + (0.03 \text{ g/hp-hr} \times 0.9 \% \times 20 \text{ hr} \times 4500 \text{ hp} \times 36 \text{ locos}) = 379.1 \text{ kg/day} \) (53\% reduction) [3]

Total NOx Emissions: \(1.3 \text{ g/hp-hr} \times 1.02 \% \times 20 \text{ hr} \times 4500 \text{ hp} \times 72 \text{ locos} = 8592.5 \text{ kg/day} \) (61\% reduction) [3]

Return on Investment: \(\$153,600,000/x \text{ days} = \$3,600,668 \) (difference in current and expected profits) \(\Rightarrow x = 43 \text{ day ROI}\)

**Systems Diagram**

Figure 9: A systems diagram explaining the inputs, outputs, and processes of the solution used to transport freight from Cincinnati, Ohio, to Pittsburgh.
Figure 10: A systems diagram representing the inputs, outputs and processes of the design used for the locomotives transporting coal from Frankfort, Kentucky to Pittsadelphia.

The systems diagrams shown above in figures 9 and 10 illustrate the details of the design for the solution. There are two separate systems diagrams for our design because we used different solutions for coal-carrying locomotives and freight-carrying locomotives. The systems diagrams show the different processes, inputs, and outputs of each individual solution.

Concept of Operations

Figure 10: A concept of operations visually representing the workings of the design.
Conclusions

Our team’s BioUpgrade solution, to run 18 freight trains to and from Cincinnati, Ohio and to run 12 coal trains to and from Frankfort, Kentucky, met or exceeded all of our user needs. We not only met the EPA standards and drastically reduced smog in Pittsadelphia, but also increased freight capacity and daily profits. Because of this, we are confident that it will satisfy all stakeholders.

From here, our design could be tested using complex simulations, and reconsidered based on test results. Some factors to consider during these tests are whether or not the current infrastructure could handle the added mechanical stress of 10 extra trains per day, and whether or not such traffic could be coordinated. Assuming the success of these simulations, implementation and real-world testing of the solution would begin to evaluate the same factors. Additionally, we would issue a survey to determine the public’s opinion on the reduced smog levels and overall opinion on the new solution. We would take this feedback and incorporate it into requirements for improvement on the design.

Throughout this project, our team gained valuable knowledge about working with real-world companies and problems. We dealt with constraints that were far more open-ended than the DEM project, and we weren’t always able to receive answers to our questions. Instead, we learned to work with these ambiguities and still create an effective solution. Additionally, we learned several new tools to assist us in the design process including an AHP matrix, the TASC concept selection method, cost-benefit analysis, systems diagrams, and concept of operations. The AHP matrix taught how to find the importance of each of our customer needs, which helped us choose which method met our most important user needs the best. We also learned a new way to assess the creativity of our designs through the TASC concept selection matrix. Additionally, the cost-benefit analysis also helped us analyze the quality of our design by allowing us to calculate important variables of our design such as the cost of the return on investment and the
environmental impacts of our design. The systems diagram and concept of operations taught us how to better communicate the details of our solutions in a simple, visual manner. All of these new methods will help us with the design process in the future.

References


