Environmentally Schwifty
City of Philadelphia
Engineering Design 100
Section 025
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14 December 2015
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CNG Engine + Fueling Station
Executive Summary or Abstract

This project was addressed with finding a transportation solution that both reduces smog to reach certain EPA guidelines as well as to maintain the freight capacity of the current system of 165,000 tons [1]. In order to do this, the first step was to clearly define the problem in context of the location, of Philadelphia, and then to develop a series of relevant customer needs to address in the final product. An Analytical Hierarchy Process (AHP) matrix was used to determine the importance of each of the customer needs. From brainstorming, several potential ideas were generated, and then put through both the Tool for Assessing Semantic Creativity (TASC) and a Concept Selection matrix to gain a better insight as to the idea to most seriously consider. Through those assessments, it was determined that the most likely idea to progress from was to simply change the 50 locomotives within Philadelphia to use Compressed Natural Gas (CNG) as a fuel source. By doing both a cost-benefit analysis and an environmental analysis, it was determined that this proposed design fulfills the initial goals by reducing NO\textsubscript{x} by 50% and particulate matter by 95%, and it maintains the freight capacity such that there is an expected return on investment of 2.07 years [5].

Introduction and Problem Statement

Philadelphia would like smog from transportation to be reduced in the city so that the public safety and health is greatly increased. Currently, Philadelphia has 50 trains carrying 165,000 tons of materials, which causes air pollution and public unrest [1]. The
pollution can ultimately lead to reduced visibility as well as numerous health issues such as lung cancer and upper respiratory problems. We will assess using alternative, and more environmentally friendly fuel sources in addition to employing more effective after-treatment hardware. This will be done while maintaining or improving both costs and freight capacity. Research will be done comparing emissions and fuel types, analyzing costs to benefits, and surveying public opinion to ensure that these accomplishments are appropriately fulfilled.

**Background**

Every day into and out of the port city of Philadelphia, approximately 165,000 tons of freight or minerals (coal, etc.) per day travel via rail [1]. Smog from locomotive emissions is a key complaint of city residents. Smog is generated from engine-emitted NOx. Tier 2 locomotives used to haul freight are approaching age for overhaul, at which time investments will be required to meet EPA Tier 3 (or higher) requirements [1].

**Customer Needs**

Our group came up with the following important customer needs:

1. The means of transporting cargo is of equal or lower cost.
2. The method of transporting cargo meets Tier 3 or better of the EPA's requirements.
3. The cargo transported is of equal or greater capacity.
4. The delivery of the cargo is on time.
5. The same or less energy is required for the same amount of output.
6. The engine is easy to maintain or replace parts.

7. There are less than 10 accidents surrounding the new method.

8. At least half of the public believes the new device to be aesthetically pleasing.

These needs were further specified to yield quantitative data so we would be able to test the effectiveness of our design in order to meet our customer needs. Table 1 provides the associated specifications for each customer need.

Table 1. Each customer need was given acceptable and ideal specifications so each need could be assessed.

<table>
<thead>
<tr>
<th>Need</th>
<th>Acceptable Specifications</th>
<th>Ideal Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>The money invested is received back within 5.5 years</td>
<td>The money invested is received back within 2 years</td>
</tr>
<tr>
<td>EPA Smog Guidelines</td>
<td>Meets Tier 3 requirements</td>
<td>Meets Tier 4 requirements</td>
</tr>
<tr>
<td>Freight Capacity</td>
<td>165,000 ton capacity</td>
<td>180,000 ton capacity</td>
</tr>
<tr>
<td>Time Efficient</td>
<td>Gets to the customer on the expected date</td>
<td>Gets to the customer before the expected arrival date</td>
</tr>
<tr>
<td>Energy Efficient</td>
<td>Equal energy is required for the same amount of output</td>
<td>Less energy is required for the same amount of output</td>
</tr>
</tbody>
</table>
Table 2. The AHP Matrix aids in showing weight or importance of each customer need.

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>EPA Smog Guidelines</th>
<th>Freigh Capacity</th>
<th>Time Efficient</th>
<th>Energy Efficient</th>
<th>Durability</th>
<th>Safety</th>
<th>Public Opinion</th>
<th>Total</th>
<th>Weight</th>
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<tbody>
<tr>
<td>Cost</td>
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<td>0.25</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>0.25</td>
<td>0.5</td>
<td>1</td>
<td>8.00</td>
<td>0.09</td>
</tr>
<tr>
<td>EPA Smog</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>16.00</td>
<td>0.19</td>
</tr>
<tr>
<td>Guidelines</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freight Capacity</td>
<td>1</td>
<td>0.3333333333</td>
<td>1</td>
<td>0.66667</td>
<td>1</td>
<td>0.25</td>
<td>0.2</td>
<td>2</td>
<td>6.45</td>
<td>0.08</td>
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<tr>
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<td>1.499925</td>
<td>1</td>
<td>1.5</td>
<td>1</td>
<td>0.5</td>
<td>1</td>
<td>8.00</td>
<td>0.09</td>
</tr>
<tr>
<td>Energy Efficient</td>
<td>0.333333</td>
<td>1</td>
<td>1</td>
<td>0.66667</td>
<td>1</td>
<td>0.25</td>
<td>2</td>
<td>0.25</td>
<td>7.25</td>
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<tr>
<td>Durability</td>
<td>4</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>16.00</td>
<td>0.19</td>
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<tr>
<td>Safety</td>
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<td>5</td>
<td>2</td>
<td>4</td>
<td>1</td>
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<td>Public Opinion</td>
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<td>5.67</td>
<td>0.07</td>
</tr>
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</table>

From the AHP matrix we can tell what is most important to consider in our design. The most important customer needs are safety, durability, and EPA smog guidelines since they obtained the highest weight. These were ranked the most important because the goal of the project is to lower the emissions of the trains. Also, safety should always be a high priority when people are involved as well as how long the product lasts. The least important customer needs are public opinion and freight.
capacity. Although these should still be considered they were ranked the lowest completely based on the comparisons to other needs.

**Concept Generation and Concept Selection**

For the concept generation, we used the TASC method, which helped analyze, which idea was most creative and innovative. From there, we looked at the ideas more in depth, and discussed the customer needs related to each idea, as well as the cost of the implementation of the ideas. We decided not to follow the TASC method, and instead went with a different idea just because TASC did not take into account the entire list of customer needs [3]. Some of our ideas included using other modes of transportation, such as planes or ships. We decided that these were not sufficient because it would increase the delivery time, and they wouldn't necessarily be cheaper or reduce smog emissions. We also considered upgrading the locomotives from tier two, to tier four along with using a different fuel. That didn't pass through because the cost would be too much, and our return on investment would take longer. Another idea we had was to alter trucks to make them environmentally efficient, however this would again, increase the delivery time. One of our top three ideas that came up on the TASC method, was to use planes, trains, and boats as our method of delivery, while upgrading 25% of the trains to Tier 4, and using liquified natural gas (LNG) and CNG on ships. We didn't go with this idea because it was too expensive to use all of the modes of transportation, along with upgrading it. Our second top idea was to upgrade the locomotives from Tier 2 to Tier 4. We didn't go with this idea, because the time for
return on investment would be longer, and it was too costly. Another one of our top ideas was to use a plane that uses LNG or CNG, and locomotives that either use LNG or CNG. We didn’t go with this idea, because we decided we wanted to only use one method of transportation. As well as, using planes would make the delivery time longer. We also didn’t want to use LNG, for it’d be too costly to find a storage container that allows the fuel to be at a certain temperature.

For the concept selection, we discussed the customer needs, and which idea would fit best with all the needs. We went through each design, and researched on how much each design costs, how durable it would be, and what the reduction in pollution would be. From our research, it was discovered that our best idea would be to change the engine to CNG, because it best fit the EPA requirements, and the cost for implementing this idea was cheaper than the other ideas.

Cost-Benefit Analysis

The starting costs were found by taking the assumed costs given by GE of upgrading the 50 trains to take CNG fuel and a new fueling station. This totaled $1.05 billion by adding the $1 billion cost of the new fueling station and $1 million per train for the upgrade. The way the city of Philadelphia would make its’ money back would be through savings on fuel costs and savings on an emissions tax. The assumption is that GE pays the tax that the U.S. government has made for high emission emitting companies [2]. From research on types of fuels, we found that CNG is 3% more efficient. We also found that diesel costs $2.50 per gallon and CNG costs $2.12 per
gallon [9]. We took the efficiency and applied it to find the percent saved on gas. The equation is as follows: 2.5 - (2.12(.97))/2.5 = 0.17744. This means 17.744% will be saved on gas. GE for each type of train gave the yearly cost of fuel. We took these numbers and found out what we would save on gas yearly by multiplying the numbers by 365 (days in a year) and .17744 (percent saved on gas). When added this gives an annual savings of $30,572,601.50. We then calculated the amount saved by reducing carbon dioxide emissions. CNG can reduce carbon dioxide emissions by 30%. Research showed the U.S. would tax $23.35 per ton of carbon dioxide produced and $24.88 in 2017 [2]. We added these together, divided by two, and multiplied by .3 to give the amount saved per ton of carbon dioxide released. This came out to $7.23 saved per ton of carbon dioxide. Based off of further research we found that our coal and freight trains would weigh 16,710 tons and 9,800 tons on the way to Philadelphia, respectively. This was based on research that said a locomotive weighs 210 tons, a 100-ton capacity rail car weighs 34 tons, each coal train is carrying 12,000 tons, and each freight train is carrying 7,000 tons [7,8]. We compared emissions of other trains to find that a train emits .61 tons of carbon dioxide per ton [4]. This allowed us to multiply the number of trains of each type by their respective weight and the emissions per ton to give the total amount of carbon dioxide produced per day. This was then multiplied by 365 days and the savings of $7.23 per ton of carbon dioxide to give a total of how much was saved. A replica calculation was done for the trip home but using the weights of just the locomotives and railcars. The money saved on emissions totaled $476,649,788. This was added to the amount saved on fuel to give a total of $507,222,389.50 a year. To
find the time to get the investment back we took the investment amount and divided it by the amount saved per year. This gave us a return on investment of 2.07 years, which is roughly two years and one month.

**Design Review**

The first prototype consisted of only alternating the fuel from diesel to compressed natural gas (CNG). Based on the cost of changing the fuel source for all of the locomotives, the estimated total cost of CNG, and various tax breaks compared to the current cost, the estimated return on investment would be 5 years and a month. Based on research, it was determined that there would be a reduction of approximately 30% of decrease in CO$_2$ emissions [4].

The first set of feedback was relatively positive. It was suggested that we continue with the prototype but consider a combination with another mode of transportation or look into a cheaper fuel source to reduce fuel emissions.

The second set of feedback brought forth variables to consider. It was suggested that we find a way to shorten the time of our return on investment. One variable that isn’t factored into the return on investment is fluctuations in fuel cost. In order to potentially shorten the return on investment time, we would need the fuel to not cost too much. We also didn’t have a specific location for the fueling station, therefore, it was suggested that we look into specific cities, which could potentially help with decreasing the return on investment. The feedback also helped us figure out that the more frequent stops our locomotive had, the longer the delivery time.
Looking back on the feedback we made a few adjustments to our model. First we looked into cheaper fuel sources such as LNG. However, we did not decide to change from CNG to LNG because of the difference in cost reduction. LNG requires a storage container that is high in cost, in order to keep the fuel in the right temperature. Therefore, we continued using CNG as the fuel. We also looked into upgrading the trains to tier four, and selling the ones we had. Except that put us back on the previous ideas we came up with, and the cost difference wouldn’t be the same. We’d essentially make more money using CNG, and the return on investment would be sooner.

This Design Review helped us decide on the missing variables, such as the pit stop for a fueling station. The distance from the fueling station to our customer was also critical to our return on investment. We calculated distances from New York, to Philadelphia with a coal city in the middle for fuel. We tried starting from a coal city, stopping at another for fuel, and then returning to Philadelphia. We looked at cities in New York, Illinois, Pennsylvania, Rhode Island. Finally, we decided on starting at Chicago and ending at our customer in Philadelphia, which totaled to around 762 miles. We then had to take a fueling station into consideration, and we decided on having it just outside Pittsburgh. So our trip would essentially be from Chicago, to Pittsburgh, to Philadelphia, and then back again. This helped us calculate our return on investment more in detail, which then changed the ROI. The return on investment changed from 5 years, to about 2 years, which is a significant difference.
Description of Final Design

For our final model, we are looking towards reducing pollution by changing the engine to CNG.

By using a CNG engine, we’d meet the EPA smog requirements. The cost of fuel for the locomotive would also reduce by about 50% [6]. The freight capacity isn’t affected by the change in engine. Therefore, the freight capacity would still be able to transport 165,000 tons, by the estimated delivery date. Changing the engine to CNG, would not affect the noise from the locomotive, because the tracks, or vibrations from the train affect the noise. The change in fuel will benefit the residents surrounding the rail lines, because there will be much less pollution than there already is. Since the CNG fuel does not contain lead or sulfur, the amount of pollution caused by a CNG engine is much less. By using the CNG engine, we’d essentially reduce CO$_2$ emissions by 20-30%. NO$_x$ emissions would be reduced by 50%, and particulate matter reduces by 95% [4].

Given that it will only take slightly over two years to get the initial investment, we believe this is an excellent use of money in order to achieve the goals of reducing emissions by tier three standards.
Systems Diagram

Tier 2 Locomotives

Upgrade to Alternate Fuel (CNG)

Money ($50 Million Total)

Labor

Reduced CO₂ emissions by 20-30%

Reduced NOₓ emissions by 50%

Reduced Particulate Matter by 95%

Money ($1 Billion Total)

CNG Fueled Locomotives

Travel

Cargo: Coal

Freight Pick Up

Alternate Fuel Station

Travel

Delivery
Concept of Operations

Starts in Chicago

Gets Freight or Coal from Chicago

Stops in Philadelphia

Fueling station outside Pittsburgh

Unloads freight in Philadelphia

Conclusions

Based on the problem, various ideas were generated and considered, requirements were formed, and a solution was developed. Due to the air pollution and the negative effects on the people of Philadelphia, we developed conditions that the solution need to coincide with. Our final solution was to upgrade the fuel from diesel to CNG for the 50 locomotives. Of the important conditions created, we valued the safety, durability, and meeting EPA requirements the most. The CNG fueled locomotives are similar to that of the diesel fueled and so the locomotives would meet our safety requirement. The use of CNG as fuel instead of diesel results in the diesel engine being replaced with a CNG engine. The CNG engine would be newer and last longer than the
original diesel engine would at this point in time. Along with the safety and durability requirements, the EPA requirements would be met. The requirements of the EPA from tier 2 to tier 3 require a 50% reduction in particulate matter. The use of CNG as fuel surpasses the tier 3 requirements because particulate matter would reduce by 95%, NO\textsubscript{x} emissions by 50%, and CO\textsubscript{2} emissions by 20-30% [5].

Although the solution seems relatively simple, of the ideas we generated, it was the best solution. Although there was not a significant improvement in public opinion, there was no decrease in approval. Safety, freight capacity, and delivery promptness were not sacrificed when implementing the solution. The EPA requirements were greatly surpassed which significantly decreases the smog and its inconvenience on the people of Philadelphia to resolve the basis of the problem. The return on investment of 2 years and about a month is fairly short and is close to the time GE had desired of 2 years.

In the future, we believe current solution will provide for an easier transition to meeting EPA tier 4 requirements when the time comes. GE would have been making a profit by the time tier 4 requirements must be met as opposed to more recently receiving their full return on investment or still receiving their return on investment. The reduction in smog emission from changing the fuel to CNG would already be close to the tier 4 requirements and should hopefully require fewer and cheaper improvement than that of locomotives that are only meeting tier 3 requirements when tier 4 requirements are implemented.
The main lesson that we learned was to do our research. Prior to selecting the main design, research was used to further investigate various ideas and ultimately select which to develop further. Research also enabled us to make calculations and shorten our return on investment. We were able to find general percentages and averages, which were used in our calculations along with finding numerous tax breaks to save on costs and significantly decrease our return on investment time.
References


