An application of liquid pipeline optimization through parametric studies
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ABSTRACT

Pipeline optimization software focuses on finding a single optimal operating scenario for a given pipeline configuration. How the system behaves over ranges of particular parameters, however, is typically left unstudied. In this paper, I utilize an explorer tool to extract various subsets of the solution space for a liquid pipeline model currently optimized through commercial pipeline optimization software. Analysis of these subsets reveals unexpected system responses to changes in control variables, the knowledge of which can be exploited in operational planning. Additionally, knowledge gained through the parametric studies may be utilized to calibrate the optimization to achieve further reduction in operational costs.

Furthermore, the solution space produced by the pump combinations is many-dimensional. The addition of other variables increases the dimensionality even further, causing the solution space to become even more unwieldy and impossible to view graphically.

The idea behind parametric studies is simple yet powerful: vary one or more parameters through a range of values and see how the system responds to these changes. The ability to view even a subset of the solution space yields a great deal of knowledge about the system. First and foremost, parametric studies provide knowledge of the continuity and smoothness of the system. If the output variable chosen is related to power or cost, the continuity and smoothness of the objective function can be studied. Irregularities and discontinuities in the objective function make the minimization problem more difficult to solve. An additional advantage to parametric studies is the ability to find local minima. These local minima, which due to non-hydraulic reasons may be useful to the user, may or may not be near the absolute minimum that is hopefully reported by optimization software. As it is not possible to encompass every last detail about a pipeline within optimization software, the knowledge of other local minima may reveal solutions that are equally or more appealing to users than the absolute minimum. Lastly, these parametric studies may reveal unexpected system responses that were previously hidden to the user. Some system responses will be expected (e.g. a rise in operational cost as the target flow rate is increased), but other system responses exposed by a parametric study may not be as intuitive (e.g. a rise in operational cost when the suction pressure set point on a particular station rises above a certain threshold). The unexpected system responses found through parametric studies open the door to more study and understanding than a single optimal solution.

INTRODUCTION

The goal of most liquid pipeline optimization software is to find the pump operations that will minimize the operational cost of the pipeline system, given a large set of data that describes the setup and constraints of the system. Commonly, the pump operations along with possibly a few other variables make up the solution set that is sought after, and all other parameters of the configuration are held constant through the simulation. If one wants to vary a parameter outside of the solution set, this has to be done manually by simulating each value individually. In addition, the solution given by said software is a single minimal solution produced by the setup and constraints. This has the clear disadvantage in its lack of knowledge of how the objective function behaves near the minimum or in other regions of the solution space.

A great deal of research has been conducted in the pipeline optimization field, most commonly focusing on optimization algorithms. Dynamic and nonlinear programming methods have been studied on water pipelines [6] and on gas pipelines since the late 1960s [1]. The highly popular genetic algorithms [2] and evolutionary algorithms [3] were first applied to pipeline optimization in the 1980s, and these methods are still
frequently used in both liquid and gas pipeline optimization solutions. While some research addresses reductions in the search space, none has taken such a direct look at the solution space in this manner. The flexibility of such a tool additionally allows one to study in detail the optimization of pipeline operations based on parameters that may have been previously required to remain constant during an optimization simulation.

In this paper, I perform two parametric studies on the two models described in the following section. The first parametric study varies the location of a station, while the second parametric study varies the DRA injection rate at one or more stations in a model. For each individual simulation performed in a parametric study, the optimal pump operations are found that minimize the total operational cost of the system, where the total operational cost is defined to be the sum of the on-peak and off-peak electric and demand costs, DRA costs, and heater power costs accumulated during the simulated time period. The parametric studies are performed through a pre-release version of the liquid pipeline optimization software PipelineOptimizer® from Energy Solutions International, Inc. [5]. Graphics are produced through the numerical computation and visualization software GNU Octave [4].

In the next section I describe the two models utilized in this study. The following two sections describe the setup and results from each parametric study, namely Station Location and DRA Injection Rate. Finally, a discussion on the results of the studies is given.

**P pipeline Models**

Through the remainder of this paper, two different liquid pipeline models are studied using parametric studies. This section introduces these models by giving an overview of the configurations used to model these pipelines. The first model is a simple pipeline with few elements, chosen for the ease of graphically visualizing results of the parametric studies to better understand the underlying solution space. The second and main model is a more complex pipeline with many elements, from which a subset of elements are chosen for study in this paper.

**Model A**

The first liquid pipeline model that will be investigated, Model A, is a simple single-shot configuration with few elements and a simple but uphill ground elevation profile, climbing around 6000 feet in 300 miles. The simplicity of this model allows readers to graphically view results of many parametric studies, greatly enhancing the understanding of the underlying solution space.

The graphical configuration that represents Model A can be seen in Figure 1. This 300 mile pipeline consists of two pumping stations with two fixed speed electric pumps each, a heater before each pumping station, a single supply point, and a single delivery point. The fluids being moved through this pipeline are refined products, and a drag reducing agent (DRA) is injected at each pumping station. The heaters in this model are set up to increase the temperature of the fluid by a set amount. The power contracts, which are used to compute operational costs, are set up with two peak periods during the day, and on-peak and off-peak demand and energy prices are configured in the model to compute the electric costs. Pressure boundaries are used both at the supply and delivery of the line. This model simulates five days of operation with batch repetition. The capacity of the system with the given refined products ranges from 835 bbl/hr to 1036 bbl/hr, the exact capacity value depending on the fluids in the line. The target flow rate chosen for these studies is 750 bbl/hr, which is achievable for the given fluids as it is less than the minimum

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**Figure 1 – Configuration for Pipeline Model A**

**Figure 2 – Configuration for Pipeline Model B**
capacity value.

Model B

The main liquid pipeline model utilized in this study, Model B, is a more complex single-shot line. The complexity of this model opens up the possibility for very interesting results from the parametric studies. In order to achieve visual representations of the parametric study results, not all available variables are chosen in each study, which in turn reduces the dimensionality of the study. The ground elevation profile in this model features a steady increase in elevation from the beginning of the line to the end.

The graphical configuration that represents Model B can be seen in Figure 2. This 70 mile pipeline consists of four pumping stations, the first being a combined station of two booster pumps and three regular pumps, represented by two separate stations in the configuration, followed by three three-pump pumping stations. Both fixed speed and variable speed electric drivers are represented in this model; the pumps in the booster station used fixed speed electric drivers, while the remaining pumps employ variable speed electric drivers. Additionally, this pipeline model features three heaters, a resistance device to represent additional resistance from station piping, a single supply point, and a single delivery point. The fluids moved through this line are crude products, and DRA is injected at each pumping station. The heaters in this model are set up to increase the temperature of the passing fluid by a set amount. The power contracts contain a single peak period for each day of the week, and energy prices are configured in the model for the purpose of calculating operational costs for the pipeline. Pressure boundaries are used at both the supply point and delivery point of the line. The ground elevation profile in this model features a steady increase in elevation with many high mountains encountered through the lengths of the line. This model simulates five days of operation with batch repetition. The capacity of the system with the specified crude products ranges from 2705 bbl/hr to 3626 bbl/hr, the exact capacity value depending on the fluids in the line. The target flow rate chosen for these studies is 2600 bbl/hr, which is achievable for the given fluids as it is less than the minimum capacity value.

PARAMETRIC STUDIES: STATION LOCATION

The first parametric study performed in this paper explores varying station locations along the pipeline for Model A and Model B, where the output variable captured will be the total operational cost for the pipeline. The total operational cost is defined to be the sum of the on-peak and off-peak electric and demand costs, DRA costs, and heater power costs accumulated during the simulated time period. This study will be executed through changing the pipe lengths on each side of the station along with the elevation of the station. While it is unrealistic to move an existing station location on a pipeline, one may plan to add a new station to a line, or alternatively may be planning a new pipeline entirely. Either of these situations would benefit from such a study on station locations. The results of this study are highly dependent on the pipeline as a whole, especially the ground elevation profile and resulting gradeline. While it is hard to guess what the expected system response will be in this case, a relationship between the ground elevation profile and the cost profile of the system would be a reasonable expected response.

Model A

In this parametric study for Model A, I vary the station location for Station 1 (the middle station in the configuration) while measuring the total operational cost for the system. The details of this setup can be found in Table 1 (Study 1).

![Figure 3 – Operational Cost Response for Station Location, Model A](image)

The original location of this station is milepost 200, which ends up being close to the highest costs found in the parametric study, the results of which are shown in Figure 3. Recall that the ground elevation profile in this configuration is relatively simple and uphill. The minimum operational cost that is found when the station falls between mileposts 165 and 225 is $33,100.25 over the five simulated days, which occurs at milepost 170, a 9.8% savings over the original station location.

One interesting feature found in the results of this study is the two “levels” of cost in the resulting plot, averaging around $33,500 and $36,500. A quick look into the simulations that produced these costs point towards the fixed speed pump drivers being used. When Station 1 is located between
mileposts 165 and 180, only two of the four fixed-speed pumps are used for the majority of the simulation. When Station 1 is located further down the line, e.g. at its original location of milepost 200, three of the four pumps are used for the majority of the simulation. Since the pump drivers in this pipeline are fixed speed electric drivers, this forces a near-fixed increase in cost, which explains the sharp increase in cost around milepost 186.

Another interesting feature is the large drop in operational cost between mileposts 207 and 212. A look into the simulations here show that, when compared to mileposts just before and just after this region, Station 1 is able to run either just one or no pumps during most of the simulation to get over the small peak in the elevation. If the station is moved upstream in the line, it has to push harder to get the fluid over the peak, and if it is further downstream in the line, Station 0 has to work harder as well to get the fluid to Station 1. If, for non-hydraulic reasons, Station 1 must be past milepost 200, this region will give the operators the lowest operational cost for the system.

However, if this pipeline will be utilized at many different flow rates, this may not be the best location for this station after all. The previous study was performed with a target flow rate of 750 bbl/hr. One may wonder how the station location affects total operational cost for other target flow rates as well. To this end, I perform a parametric study varying both the location for Station 1 and the target flow rate at which the pipeline operates, the results of which are shown in Figure 4 and Figure 5.

The setup for Study 2 can be found in Table 1. Figure 4 shows a plot of the total operational cost of the system when the target flow rate and the location of Station 1 are varied. Figure 5 shows slices of the 3D plot at each target flow rate studied in the parametric study. One obvious conclusion from the plot in Figure 4 is that a lower target flow rate results in a smaller total operational cost of the system. Additionally, as the target flow rate increases, the steep increase in operating costs that occurs around a target flow rate of 700 bbl/hr is easily explained by the use of fixed speed electric drivers in this model’s stations. The strength of this effect, however, can clearly be influenced by the location of Station 1. When the station is closer upstream in the line, the increase in cost is smoothed out more than when the station is located further downstream in the line. However, for the target flow rates studied here, a station location near milepost 170 appears to give a low total operational cost for any target flow rate between 600 and 750 bbl/hr. Although each flow rate has its own minimum cost produced at a station location that does not match the locations for the other flow rates, a station location of milepost 170 yields a cost comparable to individual minimums for each flow rate.

Model B

For this parametric study, I vary the station location for Station 1 in Model B and investigate the response of the total operational cost for the system. The details for this setup can be found in Table 2 (Study 3). A wider range of mileposts than what is shown here was examined in the original study, but the simulation results showed that many of those station locations resulted in the target flow rate being hydraulically unfeasible, and thus were removed from the results shown below.
The results of Study 3 are shown in Figure 6. The original location for Station 1 is milepost 25.725, which is quite close to the least expensive location for this station along the line. This location is found within a trough of values between mileposts 24 and 26. The absolute minimum in this range of mileposts is a total operational cost over the five simulated days of $125,937.80, found at milepost 24, a 1.7% savings over the original location. There are two peaks in the ground elevation profile of this configuration which occur at mileposts 29.7 and 34.59. In this study, once the station location reaches the first peak, the operational cost rises significantly, as the stations upstream are forced to work much harder to get the fluid to flow past such a high elevation downstream.

As with Model A, if this pipeline will be utilized at many different flow rates, this may not be the best location for this station. The previous study was performed with a target flow rate of 2600 bbl/hr. What happens if the pipeline is operated at different target flow rates? In order to better understand this problem, I perform a parametric study (Study 4) in which I vary both the Station 1 location and the target flow rate, the results of which are shown in Figure 7 and Figure 8.

The setup for Study 4 can be found in Table 2. Figure 7 shows a plot of the operational cost response to varying station locations for Station 1 and target flow rate. Figure 8 displays 2D slices of Figure 7 at each target flow rate used in the parametric study. As in Model A, a higher target flow rate results in expected higher total operational cost. What is interesting here, which is not what was seen in the study on Model A, is that there is a pretty clear delineation between the mileposts that result in lower operational cost versus higher operational cost for all target flow rates studied. Mileposts 22 through 27 give low operational cost, while mileposts larger than 27 make the operations of the system more expensive. The ground elevation profile clearly has a large influence in the results of this study, which are invariant to the target flow rate. Additionally, while this model employs both fixed speed and variable speed electric drivers, the majority of the drivers are variable speed, which explains the lack of a sharp increase...
in operational cost as the target flow rate is increased.

**PARAMETRIC STUDIES: DRA INJECTION RATE**

The second parametric study explored in this paper will investigate the effect of DRA on the overall operational costs of the pipeline for Model A and Model B. Again, the total operational cost is defined to be the sum of the on-peak and off-peak electric and demand costs, DRA costs, and heater power costs accumulated during the simulated time period. The injection of DRA into the fluid reduces the turbulence in the hydraulic system, allowing the fluid to flow more smoothly. This in turn increases the capacity of the system, meaning that for the same flow rate, the pumps will not have to work as hard to move the fluid from the supply point to the delivery point. The expected system response for the addition of DRA to the system is an initial decrease in cost as the fluid viscosity is decreased. Eventually, as more DRA is introduced into the system, the effect of the DRA is greatly reduced and it cannot affect the fluid hydraulics significantly. At this point the cost will increase linearly due to the additional use of ineffective DRA. Both Model A and Model B simulate the effect of DRA in the fluid through the standard DRA equation, where the drag reduction factor $F$ is of the form

$$F = \frac{ppm}{A \cdot ppm + B},$$

where $ppm$ represents the DRA concentration in parts per million by volume and $A$ and $B$ are product-specific constants based on the temperature, specific gravity, and viscosity of the fluid.

**Model A**

In this parametric study for Model A, I vary the DRA injection rate at Station 0 and Station 1 while looking at the overall operational cost for the system. The details for the setup of this study can be found in Table 3 (Study 5). Figure 9 shows the operational cost response for Model A to a variable DRA injection rate at the two stations. Figure 10 displays a contour plot view of the operational cost response to the different DRA injection rates for the system.

The resulting plots show a clear difference between the lack and presence of DRA in the system. Even a small amount of DRA injected at the two stations decreases the operational cost dramatically. Beyond this initial decrease in cost, additional DRA injected into the system slowly increases the total operational cost until there is enough DRA to turn off an additional fixed speed pump. Once this threshold is reached, the total operational cost drops again, this time to the global minimum operational cost. In fact, there is a clear curve that can be seen in Figure 10 (denoted by the dashed line) along which the additional fixed speed pump is no longer required. After this final decrease in operational cost, any more DRA added into the system is unnecessary and increases the total cost linearly by the cost of the DRA. Inspection of the data reveals the minimum total operational cost over the five
simulated days to be $34,157.70. This minimal cost occurs at the optimal DRA injection rates of 70 ppm for Station 0 and 45 ppm for Station 1, a 14.6% decrease in operational cost over using no DRA in the system.

**Model B**

In Model B, all four stations have the ability for DRA injections, i.e. four different input variables, which could potentially all vary at the same time, making the visualization of the results much more difficult. While it is possible to view the results in a pivot table, this table would be entirely too large to fit in this paper. In the interest of ease of understanding and to allow the results to be viewable graphically, I choose to restrict this paper to three-dimensional studies, i.e. a maximum of two input variables at the same time with one output variable. For this specific study, as it is practical to expect a pipeline to be operated at more than one target flow rate, I choose to vary the target flow rate along with the DRA injection rate for a single station in the pipeline.

To this end, for the Model B DRA parametric study, I begin by varying the DRA injection rate for Station 0 along with the target flow rate, and examine the resulting total operational cost. The setup for this study can be found in Table 4 (Study 6).

![Figure 11 – Operational Cost Response Plot for Station 0 DRA Injection Rate versus Flow Rate, Model B](image)

Figure 11 shows the operational cost response to varying target flow rates and DRA injection rates for Station 0. Figure 12 shows slices of the 3D plot at the targeted flow rates. The resulting plots shown in Figure 12 show the highest cost to arise from the case with no DRA injected into the system, as expected. For each of the flow rates studied, a local or global minimum is reached rather quickly, and then the operational cost increases at a steady rate. As we are studying the total operational cost for the system, a change in the DRA injection rate may trigger other changes in another part of the system, which may explain the additional peaks and troughs found in the 2400 bbl/hr and 2500 bbl/hr slices found in Figure 12. For a majority of the slices, a DRA injection rate between 1.0 ppm and 5.0 ppm produces a reasonable reduction in operational cost; for 2400 bbl/hr, a DRA injection rate of 5.0 ppm would be ideal. Past this point, the additional DRA injected into the system does not meaningfully improve the hydraulics any longer, and the additional DRA cost adds into the total cost linearly.

**DISCUSSION**

Through this paper, I have demonstrated the use of parametric studies on non-traditional optimization parameters for the study of operational cost responses on a liquid pipeline system. Two variable sets were studied for two different pipeline models, namely station location and DRA injection rates. Not only are the optimal cost and the setup producing this optimum found for each variable, but a rich data set is also produced that allows one to learn a great deal about the system and its cost responses to said variables. Visualizations in 2D and 3D of these objective function subsets are given along with slices of 3D plots to enhance comprehension of the objective function for each system.
Parametric studies such as these provide a unique view into subsets of the objective function that is typically left unseen, and can provide the user with broader knowledge than common optimization software gives without significant manual work.

REFERENCES


AUTHOR

Dr. Jennifer Worthen is the Development Manager for PipelineOptimizer, a product in the Liquid Management Systems (LMS) provided by Energy Solutions International Inc. in Houston, Texas, USA. Jennifer has a Bachelor’s degree in Applied Mathematics from Texas A&M University, a Master’s degree in Computational and Applied Mathematics from The University of Texas, and a Doctorate in Computational Science, Engineering, and Mathematics from The University of Texas.

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**TABLES**

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Table 1 – Parametric study setup details for Station Location studies on Model A

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Table 2 – Parametric study setup details for Station Location studies on Model B

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Table 3 – Parametric study setup details for DRA Injection Rate study on Model A

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Table 4 – Parametric study setup details for DRA Injection Rate study on Model B