Configurable Tools for the Pipeline Scheduler
Dale Ball, Wolverine Pipeline Company.
Paul Dickerson, Energy Solutions International.

ABSTRACT

Wolverine Pipeline Company operates several product pipeline systems in Michigan, USA. Being able to efficiently schedule a line, import data, work with injections and analyze results become more important as the lines become more complex.

There are many tools available to schedule crude and product pipelines. These tools range from manual processes, such as drafted railroad charts, through configurable standard software packages to highly customized solutions.

The tools needed by a pipeline scheduler depend on the scheduling scenario and the pipeline network. For example, scheduling a point to point line can often be accomplished using an Excel spreadsheet. However, as soon as the complexity increases by, for example, the addition of a midline destination, the simple Excel spreadsheet soon becomes impractical, and programmed logic needs to be included to manage the line. Soon the scheduler is relying on a programmer to maintain the once simple system.

Increasing complexity of scheduling scenario and pipeline network can lead to alternative solutions. These include iterative steady states, transient simulation models or specialized flow rate estimation schemes which can handle logical rate changes as well as product and possibly pump sequencing. The injection of Drag Reducing Agents (DRA) to improve schedules and increase line capacity further complicates scheduling.

The focus of this paper is to compare and contrast, under different scenarios, a spreadsheet, a transient simulator and a scheduling package, for the accuracy of results, ease of use, speed and performance. An overview of the different methodologies is provided.

Keywords:
- Pipeline Schedule
- Product Schedule
- Crude Schedule
- Scheduling Logic
- Steady State Simulation
- Transient Simulation

WOLVERINE PIPELINE COMPANY

Figure 1: Wolverine Pipelines
The Wolverine Pipeline Systems consist of four pipeline systems comprising of over 1000 miles of various size pipe ranging from six inches to eighteen inches in diameter. There are twelve pumping stations with thirty four units varying from 400 to 3000 horsepower. These pump stations deliver various high-quality products to several customers at twenty-nine delivery terminals covering three states.

The largest and most complex of the four systems is the Mainline System. This system consists of ten pipeline segments that come together at a manifold station called Kennedy Avenue. Kennedy Avenue is the origin of the three outgoing segments and the termination point of the seven incoming segments. Because of the relationship of all of these segments of pipe around Kennedy Avenue it is scheduled as one system with the outgoing segments originating at Kennedy Avenue and the incoming (or feeder segments) are then scheduled backwards so that product arrives at Kennedy Avenue in time to meet the schedules of the outgoing segments.

The segments that make up the Mainline System are as follows:

**JOLIET - HAMMOND 18” SEGMENT (FEEDER)**
This segment consists of 49.5 miles of 18” diameter pipe, originating at Joliet pump and meter station and terminating at the Kennedy Avenue pump and meter station. This system operates as a closed system, in that no deliveries are made into or out of the system between the origin and destination points.

Product enters the system from the refinery and leaves the system by taking one (or more) of three routes through Kennedy Avenue station. The incoming stream can be (1) boosted through the station into the 16” mainline, (2) boosted through the station into the 16” loop line, or (3) turned through the station for deliveries to the:

- White Oak line to the ExxonMobil Terminal
- Buckeye Terminal
- CITGO Terminal

Product can be stripped to White Oak off the mainline stream going either to the mainline or the loop line.

Rates on this line vary as follows:

- Gasoline = 3000 – 9200 BPH
- Distillates = 3000 – 7800 BPH

**LOCKPORT - HAMMOND 16” SEGMENT (FEEDER)**
This segment consists of 40.7 miles of 16” diameter pipe, originating at the Lockport pump and meter station and terminating at the Kennedy Avenue pump and meter station. This system operates as a closed system, in that no deliveries are made into or out of the system between the origin and destination points.

Product enters the system from the refinery and leaves the system by taking one (or more) of three routes through Kennedy Avenue station. The incoming stream can be (1) boosted through the station into the 16” mainline, (2) boosted through the station into the 16” loop line, or (3) turned through the station for deliveries to the:

- White Oak line to the ExxonMobil Terminal
- Buckeye Terminal
- CITGO Terminal

Product can be stripped to White Oak off the mainline stream going either to the mainline or the loop line.

Rates on this line vary as follows:

- Gasoline = 3000 – 9100 BPH
- Distillates = 3000 – 7800 BPH

**LOCAL SHIPPER SEGMENTS (4) FEEDER**
There are four 16” lines that feed a separate manifold at Kennedy Avenue that is connected to the outgoing Mainline and Loopline segments only.

The segments are from:

- Explorer Pipe Line
- Buckeye Hammond
- Citgo East Chicago
- Marathon/Valero/BP Whiting

There are two exceptions to the restrictions of this manifold. The Explorer feeder has a connection that enables flow to be directed into the outgoing Kennedy to White Oak segment and
the Citgo East Chicago segment is by-directional and product from the incoming Joliet to Hammond 18” and Lockport to Hammond 16” can be directed back toward Citgo East Chicago.

The outgoing segments are as follows:

**KENNEDY AVENUE - WHITE OAK 16” SEGMENT**
This segment consists of 4.8 miles of 16” diameter pipe, originating at the Kennedy Avenue pump and meter station and terminating at the White Oak meter station where it delivers to the ExxonMobil Terminal.

Deliveries can be made to the Buckeye Terminal at the Buckeye Junction.

Product normally flows through Kennedy Avenue, from the Joliet to Kennedy Avenue 18” system into the Kennedy Avenue to White Oak 16” segment. However, it is possible to direct the Lockport to Kennedy Avenue 16” stream into Kennedy Avenue to White Oak 16” segment. In addition, products can be received from Explorer Pipeline and delivered to Buckeye Hammond or ExxonMobil White Oak.

Rates on this line vary as follows:

- Gasoline = 6000–7800 BPH
- Distillates = 5200–6500 BPH

**HAMMOND - NILES 16” LOOP SEGMENT**
The Hammond to Niles segment consists of 67.9 miles of 16” diameter pipe, originating at the Kennedy Avenue pump and meter station and terminating at the Niles pump and meter station, where products are delivered into Niles Terminals. This system operates as a closed system, in that no deliveries are made into or out of the system between the origin and destination points.

Product can be pumped into the 16” loop line from one of six sources entering Kennedy Avenue:

- 18” Wolverine pipeline from Joliet
- 16” Wolverine pipeline from Lockport
- Explorer Pipeline
- Marathon Terminal / Valero Terminal
- Buckeye Terminal
- CITGO Terminal

The 18” from Joliet and the 16” from Lockport come in one manifold and can be boosted full stream to the 16” loop line. If desired, this manifold is designed to allow for a strip operating to either the 16” segment to White Oak, the 16” segment to several local terminals, or the 16” mainline. Local shippers come into Kennedy Avenue through four separate 16” lines and into the local shipper’s manifold. These products can be stripped to the 16” loop line or the 16” mainline if desired.

At Niles, some of the product is delivered locally, while some of this product is pumped out of tankage into the Niles to Grand Haven 8” system.

Rates on this line vary as follows:

- Gasoline = 3600 – 6200 BPH
- Distillates = 3600–5100 BPH

**16” MAINLINE SEGMENT**
The 16” Mainline segment of the Wolverine Products System originates at the Kennedy Avenue pump and meter station and extends in an easterly direction to Detroit. At Jackson, the flow can be directed in a northeasterly direction for delivery of products into the Spartan System, or can continue on for delivery of products into the Detroit area. The system contains a total of approximately 260 miles of 16” diameter pipe.

There are six pump stations on the Mainline:

1. Kennedy Avenue pump and meter station
2. Michigan City pump station
3. Dailey pump station
4. Vicksburg pump station
5. Albion pump station
6. Freedom Junction pump station

All six pump stations consist of three pumping units each; a 3000hp unit, a 1250hp unit, and a 1000hp unit.

Product can be pumped into the 16” Mainline from one of six sources entering Kennedy Avenue:

- 18” Wolverine pipeline from Joliet
- 16” Wolverine pipeline from Lockport
- Explorer Pipeline
- Marathon Terminal / Valero Terminal
- Buckeye Terminal
- CITGO Terminal

There are twelve receiving terminals supplied by the Mainline at the following stations:
• Black Oak (BP Pipeline)
• Marshall (Buckeye)
• Jackson (Buckeye, Marathon, CITGO)
• Detroit Metro (Marathon, RKA Petroleum, Buckeye, BP)
• Detroit Woodhaven (Buckeye)
• Detroit Dearborn (Buckeye, Peerless-Cousins)
• Detroit Sanders (Buckeye)

Rates on this line vary as follows:

Gasoline = 3000 – 8000 BPH
Distillates = 3000 – 7200 BPH

Currently the Freedom Junction to Toledo, Ohio, segment is being leased to Enbridge and is in crude service.

NILES - GRAND HAVEN 8” EXTENSION SYSTEM

Figure 4: Extension schematic

The Wolverine Extension Line consists of 96.2 miles of 8” diameter pipe, originating at Niles pump and meter station and extending in a northerly direction to Grand Haven meter station. At Grand Haven, product must be moved an additional 1.34 miles to Ferrysburg to the following terminals:

• CITGO / Buckeye Terminal
• Buckeye Terminal

Deliveries can also be made to the Holland Terminal in Holland, 74.5 miles north of Niles.

Rates on this line vary as follows:

Gasoline = 1200 – 1700 BPH
Distillates = 900 – 1200 BPH

JOLIET - LOCKPORT 16” SYSTEM

Figure 5: Storage schematic

This segment consists of 20.8 miles of 16” diameter pipe from Jackson to Stockbridge, 11.8 miles of 12” pipe from Stockbridge to Meridian Road, 30.5 miles of 8” pipe from Meridian Road to LaPaugh, 14.6 miles of 6” pipe from LaPaugh to Lansing Terminal, 27.8 miles of 6” from LaPaugh to Alma, and 51.9 miles of 8” pipe from Alma to Bay City. Deliveries from Jackson are to breakout tankage at Stockbridge. At Stockbridge, product is re-injected to the pipeline for deliveries to the Marathon Terminals at Lansing and Bay City.

There are three pump stations:

1. Stockbridge pump station
2. LaPaugh pump station
3. Alma pump station

Rates on this line vary as follows:

Gasoline = 950 – 2600 BPH
Distillates = 750 – 1800 BPH

THEORY OF PIPELINE SCHEDULING

There are many methods by which the maximum flow rate of a pipeline can be estimated under different linefill conditions. Three commonly used methods are discussed.

Weighted Average method

The weighted average method of flow rate estimation is described thus:
The advantage of this method is that once the maximum rates for each fluid type have been determined either by simulation or by experience, it is a simple task to determine the maximum rate of any line-fill. This can be analyzed in a spreadsheet quickly, and a reasonable time step grid is used, the departure and arrival of any batch of fluid can quickly and easily be determined.

The disadvantage is that the flow rate tends to be less accurate than the more rigorous methods as it necessarily uses a number of fixed assumptions regarding the operational state of the pipeline. Additionally considerable effort may be needed to configure and identify the optimal time steps.

**Transient Simulation Method**

Transient simulators are well documented in other papers, and will only be discussed at a high level in this paper.

Equations of mass, momentum and energy are used to determine hydraulic properties in a pipeline configuration between calculation intervals over a series of time steps.

While there is much documentation alluding to the accuracy of transient simulators, they can also be cumbersome and relatively slow for the requirements of scheduling pipelines.

The reasons for this can be:

1. **Limitations to prevent instability**

   Many transient simulators have limitations to prevent them becoming unstable, for example Courant–Friedrichs–Lewy (CFL) condition is a necessary condition for convergence while solving certain partial differential equations.

2. **“Off the shelf” simulators require consideration of operational control logic.**

   The scheduler wants to schedule the pipeline and not get dragged into the nitty-gritty demands of the operational minutia.

Scheduling logic differs from the logic used in pipeline simulators. A pipeline simulator will normally mandate the user to provide logic to control the pressure, flow and temperature and inlets, the pressure and flow at outlets, and the ability to enforce hydraulic or physical restrictions in between these points. The simulator also normally “ramps” hydraulic control variables. Opening routing valves and starting and stopping pumps must all be considered by the scheduler.

3. **Engineering versus Scheduling Simulators**

   Pipelines often have complex junctions and header arrangements through which the various batches must be routed. A scheduling simulator can address these in a convenient and short-hand method conducive to quick work flow. Engineering simulators, on the other hand, by nature must deal with a more complete representation increasing the work to specify the operation and slowing down the actual simulation.

4. **Time-stepping may slow system**

   Depending on the type of time stepping used, a fixed time step will almost certainly be too slow to model a complex system. A variable time step may handle it, but anything that causes time steps to decrease will slow the system (e.g. simulation constraints, stability controls etc.). In contrast a pipeline scheduling system tends not to suffer from these issues as it is determining flow rates at longer time intervals.

However the advantages of transient simulations for scheduling are:

1. **Accuracy**

   Generally it can be expected that flow rate will be determined much more accurately using a transient simulator. This is because it allows for much smaller time intervals, and determines pipeline flow rate...
based on the full set of hydraulic variables. Variations in the control setpoints and other variable operational concerns can also be addressed. For the purpose of this paper it is assumed the transient simulation is the most accurate representation of a “real life” batch plan.

2. Full hydraulic model

A transient pipeline simulator normally uses a more complete set of hydraulic variables in the solutions, i.e. pressure, flow, temperature, density, viscosity. The model will also have a much accurate knowledge of pipeline geometry allowing a user to determine both minimum and maximum flow rates for a given linefill. This is especially true if the pipeline rate becomes bottlenecked by pump curve limitations or pump driver power limits.

Fast Steady-State Approximation Method

\[
Q = \frac{1}{\sqrt{f_1 f_2 f_3 f_4}}
\]

Where \( K \) is a product constant computed from the maximum rate and density of each product in each segment, and \( V \) is the volume percentage of this particular product in this segment.

This method makes several significant assumptions about the nature of the pipeline bottlenecks in each segment. The diameter of the pipe must remain constant, and the pipeline flow limit must be caused by the pressures reaching the upstream maximum pressure and downstream minimum pressures. Accuracy drops as the actual bottlenecks move further away from this ideal bottleneck. For example as when the discharge setpoints at the stations are adjusted.

PRACTICAL EXAMPLES

Point to Point line example

A 26 mbbls pipeline transporting Gasoline and Distillate (Joliet - Lockport line) with maximum flow rates of 9200 and 7200 respectively.

This system was modeled in a spreadsheet, a transient simulator and scheduling software to determine the accuracy of the simulation.

The simulations performed were

1. Full linefill gasoline transition in full linefill distillate
2. Full linefill distillate transition into full linefill gasoline

Figure 6: Storage schematic

Point to point example with an adjustable strip

A 36 mbbls pipeline transporting Gasoline and Distillate (Extension line) with maximum flow rates of 1200 and 1000 respectively, and with a midpoint adjustable strip.

This system was modeled in a transient simulator and scheduling software to determine the accuracy of the simulation.
The simulations performed where:

1. Full line-line fill of Gasoline transition full linefill of distillate
2. Full line-line fill of distillate transition full linefill of gasoline
3. Full linefill of distillate transition into full linefill of gasoline with 50% strip
4. Full linefill of Gasoline transition in full linefill distillate with 50% strip

Figure 7: Extension schematic

**Handling a complex logical scheduling sequence**

A complex subset of the mainline configuration was modeled in a transient simulator and a scheduling package.

The section from Joliet to Detroit was modeled for both gasoline and distillate. Pump stations were included in the transient model at frequent intervals. The mainline section is approximately 400 mbbls.

The simulation performed where:

1. Full linefill gasoline transition into full linefill distillate
2. Full linefill distillate transition into full linefill gasoline
3. Full linefill gasoline transition into full linefill distillate with 5% by volume strip at each mid line delivery.
4. Full linefill distillate transition into full linefill gasoline with 5% by volume strip at each mid line delivery.

Figure 8: Mainline schematic

**RESULTS**

**Point to Point line example**

The Excel workbook proved to provide very fast results using the weighted average method.

Chart 2: Weighted average solution showing linefill of gasoline transitioning to linefill of distillate, followed by linefill of distillate transition to linefill of gasoline.

The transient simulation is reasonably fast. The main time delay is in finding an initial state. Once this is found the simulation gets results quickly. Some estimates were made for the configuration of the model, for example whilst lengths and diameters where known, schedule and roughness where unknowns. An attempt at tuning the model was made and reasonable rates were identified. Additionally, fluid specifications where estimated for gasoline and distillate products.
Chart 3: Transient simulation solution showing linefill of gasoline transitioning to linefill of distillate, followed by linefill of distillate transition to linefill of gasoline.

The flow rate approximation method of simulation also provided results rapidly; faster than the transient simulator and comparable to the Excel workbook. The system model configuration is well understood for this case and data volumes and fluid property data are good and match those used by the transient model.

Chart 4: Fast approximation simulation solution showing linefill of gasoline transitioning to linefill of distillate, followed by linefill of distillate transition to linefill of gasoline.

Table 1: Table illustrating simulation metrics for point to point line

<table>
<thead>
<tr>
<th></th>
<th>Calculated time to complete plan</th>
<th>Simulation time</th>
<th>Configuration time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreadsheet</td>
<td>5.88 hr</td>
<td>&lt;1 s</td>
<td>1 hr setup</td>
</tr>
<tr>
<td>Transient</td>
<td>6.21 hr</td>
<td>23 s</td>
<td>10 min setup</td>
</tr>
<tr>
<td>Fast approximation</td>
<td>6.21 hr</td>
<td>&lt;1 s</td>
<td>1 min setup</td>
</tr>
</tbody>
</table>

Point to point example with an adjustable strip

It was challenging to configure a good example of this scheduling scenario in Excel. While an Excel model was created, time constraints prevented inclusion in this paper.

The transient simulation again provided fast results, and again estimates were made for geometry and fluid properties.

Chart 5: Comparison side by side of transient simulation (blue) and fast approximation simulation (red).

Note: The transient simulation data is “raw” i.e. all simulation time steps are displayed. The scheduling application does not “trend” this fine detail so only contains steps where the max time step is reached or there is a change in batch at a major location.

The fast approximation method proved extremely fast for this case. Again as the pipeline structure and operation is well understood for this implementation the data can be assumed to be good.

The fast approximation method proved very fast for this case. Again as the pipeline is well understood for this implementation the data can be assumed to be good.

Table 2: Table illustrating simulation metrics for line with adjustable strip

<table>
<thead>
<tr>
<th></th>
<th>Calculated time to complete plan</th>
<th>Simulation time</th>
<th>Configuration time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreadsheet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient</td>
<td>167.51 hr</td>
<td>24 s</td>
<td>10 min setup</td>
</tr>
<tr>
<td>Fast approximation</td>
<td>167.55 hr</td>
<td>&lt;1 s</td>
<td>1 min setup</td>
</tr>
</tbody>
</table>
Handling a complex logical scheduling sequence

The transient simulator handled this model relatively slowly. This is due largely to the need to take smaller time steps as the fluid properties changes at each delivery location. The simulator is also “fiddly” and time consuming to configure for this case as the interface is not designed with the scheduler in mind, but with the engineer in mind.

The transient simulation is accurate and reasonably fast as long as the batch plan does not require too much detail or variations that produce transients.

The fast approximation method of simulation also provided results rapidly; faster than the transient simulator but slower than the Excel workbook. The system model is well understood for this case and data volumes and fluid property data is good as compared to the transient simulation.

Point to point example with an adjustable strip

It was challenging to configure a good example of this in Excel. While an Excel model could be created, time constraints prevented inclusion in this paper.

The transient simulation again provided fast results, and again estimates were made for geometry and fluid properties.

The fast approximation method proved very fast for this case. Again as the pipeline is well understood for this implementation the data can be assumed to be good.

Handling a complex logical scheduling sequence

The transient simulator handled this model relatively slowly. This is due largely to the need to take smaller time steps as the fluid properties changes at each delivery location. The simulator is also “fiddly” and time consuming to configure for this case as the interface is not designed with the scheduler in mind, but with the engineer in mind.

The fast steady state approximation method proved exceptionally fast and adept at solving this problem. Data entry was simple as the user interface is designed for this purpose. The results are sufficiently accurate for scheduling purposes.

Point to point example with an adjustable strip

It was challenging to configure a good example of this in Excel. While an Excel model could be created, time constraints prevented inclusion in this paper.

The transient simulation again provided fast results, and again estimates were made for geometry and fluid properties.

The fast approximation method proved very fast for this case. Again as the pipeline is well understood for this implementation the data can be assumed to be good.

The fast steady state approximation method proved exceptionally fast and adept at solving this problem. Data entry was simple as the user interface is designed for this purpose. The results are sufficiently accurate for scheduling purposes.

DISCUSSION OF RESULTS

Point to Point line example

The Excel workbook proved to provide very fast results using the weighted average method. The accuracy of the results can be brought into question because of the linear behavior.

The transient simulation is accurate and reasonably fast as

<table>
<thead>
<tr>
<th></th>
<th>Calculated time to complete plan</th>
<th>Simulation time</th>
<th>Configuration time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spreadsheet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transient</td>
<td>515.23</td>
<td>46 s</td>
<td>30 min setup</td>
</tr>
<tr>
<td>Fast approximation</td>
<td>516.09</td>
<td>&lt;1 s</td>
<td>2 min setup</td>
</tr>
</tbody>
</table>

Table 3: Table illustrating simulation metrics for complex set of strips

REFERENCES

2. Engineering Toolbox
   (http://www.engineeringtoolbox.com)
3. Hydraulics for Pipeliners, C.B. Lester
4. Pipeline Rules of Thumb, E.W. McAllister
5. Engineering Mathematics, K.A. Stroud
6. Flow of Fluids through Valves and Fittings, Crane
7. PSIG0708 – Non Chronological Pipeline Analysis for Batched operations, Kevin Webb
8. PSIG 0305 – Crude Scheduling Package for an Indian Cross-country Pipeline, TRV Krishnan, KV Siva Rao, Jason Modisette, K.M. Bansal, K.K. Jain