Transient Simulation and Optimization of Natural Gas Pipeline Operation and Applications to Gas–Electric Coordination

Presented at the FERC Technical Conference: Increasing Real-Time and Day-Ahead Market Efficiency through Improved Software

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Project Team

Technical Expertise

Disclaimer

The opinions presented herein are solely those of the authors and do not necessarily reflect those of the entities of which the authors are a part or those of the full Project Team. Specifically, no opinion or conclusion expressed or implied in this document may be attributed to our cooperating entities -- the PJM Interconnection and Kinder Morgan

Outline

- About GECO, Project Team
- Gas System Optimizer (GSO) – software for transient pipeline network optimization
- Model benchmarking to SCADA data
- Numerical experiments to
  - estimate the value of transient optimization
  - estimate the potential value of the Gas Balancing Market
- Conclusions

GECO Project Summary

- Formal Project Title: *Coordinated Operation of Electric And Natural Gas Supply Networks: Optimization Processes And Market Design*
- Leading Organization: Newton Energy Group LLC
- ARPA-E Program: OPEN-2015
- Project started: April 20, 2016
- Project term: 2 years through April 19, 2018. Extended through October 2018
- ARPA-E project summary: https://arpa-e.energy.gov/?q=slick-sheet-project/gas-electric-co-optimization

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GECO Objectives and Program Elements

Objectives: algorithms, software and an associated market design to dramatically improve coordination and / or co-optimization of natural gas and electric physical systems and wholesale markets on a day-ahead and intra-day basis

Program Elements

Software & Algorithms

- Modules for pipeline simulations and optimization
- PSO SCUC/SCED for electric system simulation
- Data, cloud-based system simulating gas - electric interactions

Market Design

- Joint gas-electric theory and computation methods of granular prices consistent with the physics of operations
- Market design proposal including coordination mechanisms using granular prices

Realistic Market Simulations

- Gas-electric simulation model using realistic data
- Simulated scenarios comparing performance of gas-electric coordination policies under different assumptions

GECO Project Team and Technical Expertise

Institution	Expertise
Newton Energy Group	• ENELYTIX® Cloud platform for parallel modeling and analytics of energy systems and markets • Optimal dynamic pricing and market design • Commercialization
Los Alamos National Laboratory EST. 1943	• Advanced computational methods and algorithms for simulation and optimization of gas & electric networks
POLARIS Systems Optimization	• PSO – an advanced power systems simulation engine within ENELYTIX® • Power systems optimization expertise
Boston University	• Market design, coordination algorithms
AIMMS	• Modeling language, optimization

External Technical Expertise

pjm KINDER MORGAN

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Presented at the 2017 FERC Technical Conference

- Advancements in dynamic optimization of real-size pipeline network
- The concept of Locational Trade Value (LTV) of natural gas as Lagrange multipliers for nodal mass balance
- Introduced Gas Balancing Market (GBM) as a voluntary transparent intra-day mechanism for trading deviations from ratable nominations made day-ahead

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Gas System Optimizer (GSO)

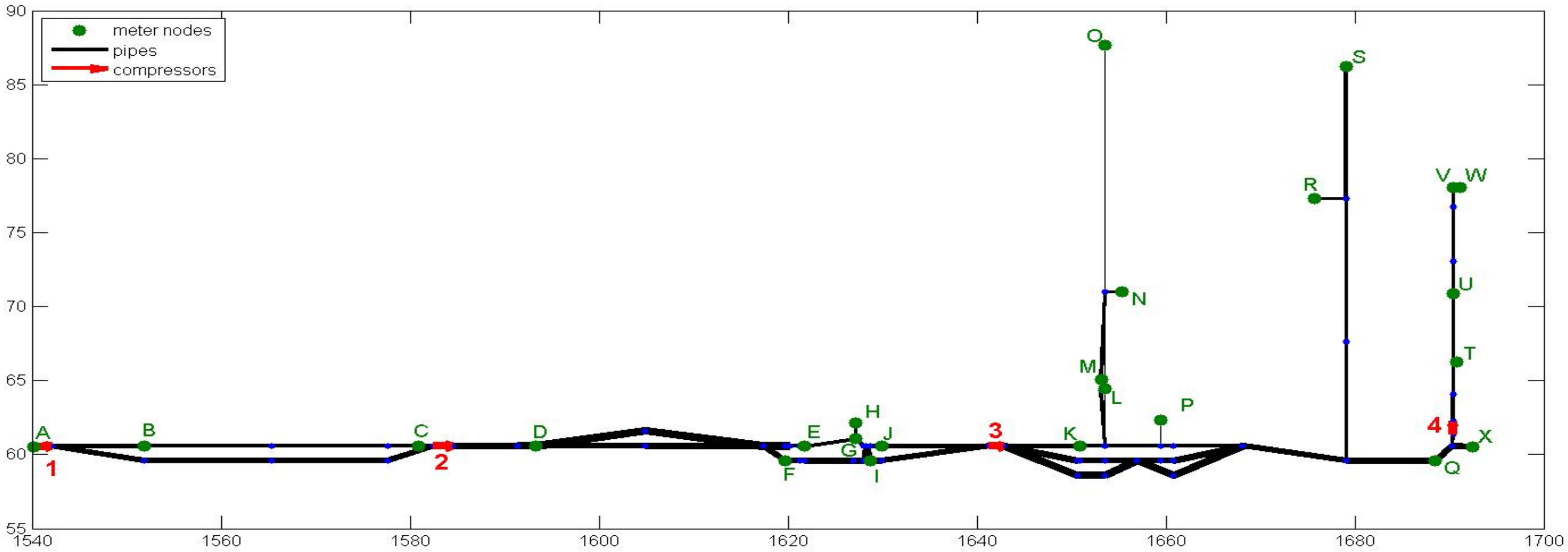
Gas System Optimizer (GSO)

- Algorithms and Matlab code developed by LANL
- Problem formulation in the context of social welfare optimization – joint development of the GECO team
- User controlled linear objective function. In addition to maximizing social welfare can maximize throughput and other linear metrics
- Runs optimization using rolling horizon approach
- Primary focus is on intra-day details over one- to several days optimization horizon. User defined time step (multi-hour, hourly, sub-hourly)
- Integrated into ENELYTIX® cloud-based parallel computing system as PSO – GSO interaction process; implemented on Amazon EC2 cloud (GSO integration and development is being finalized)
- Could be used solely for pipeline network optimization as well as for modeling coordinated operation of natural gas pipeline system and electric networks
- GSO models, algorithms, key engineering constraints – see A. Zlotnik, M. Chertkov, and S. Backhaus, "Optimal control of transient flow in natural gas networks," in 54th IEEE Conference on Decision and Control, Osaka, Japan, 2015, pp. 4563–4570

Model Validation using real SCADA Data

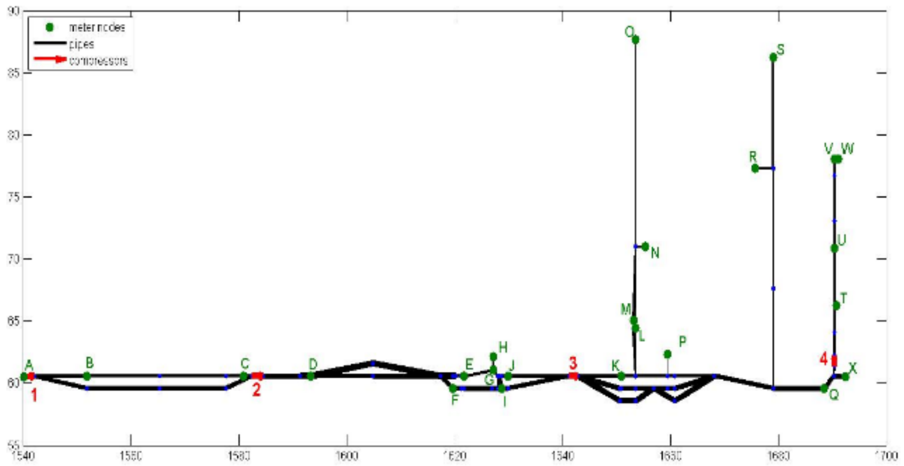
Model Validation: Real Data

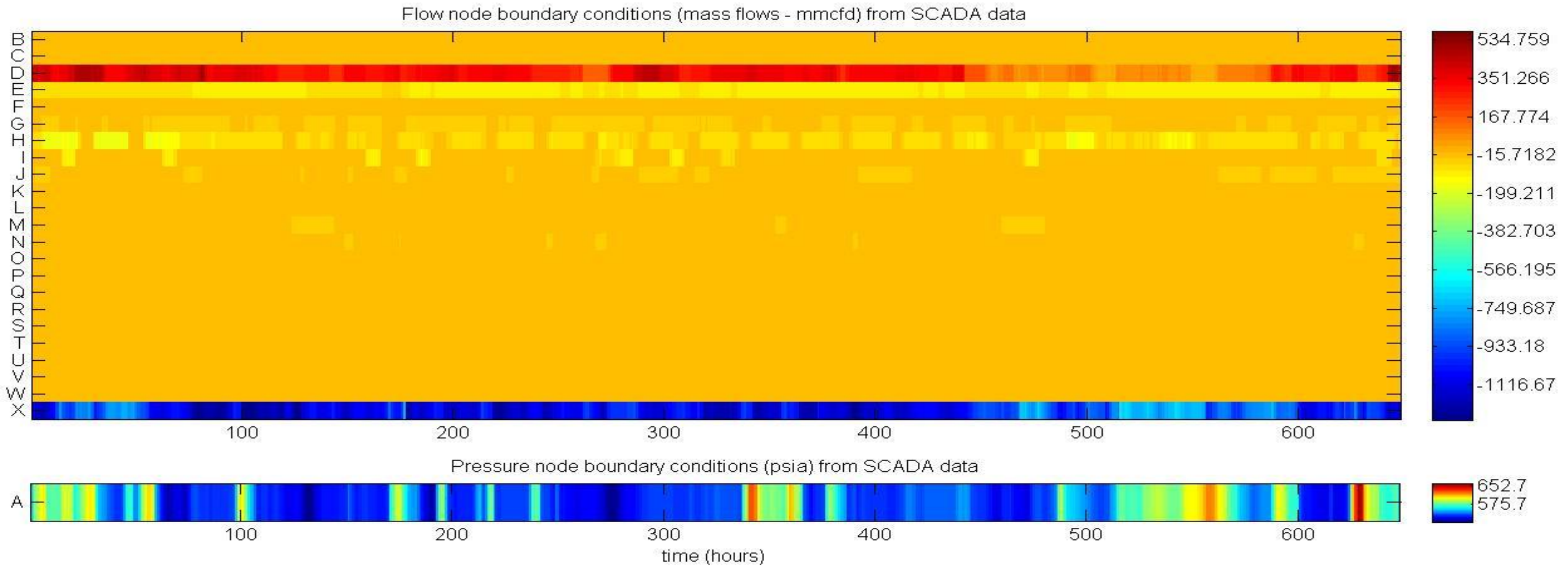
- Reduced model of subsystem:
  - 78 nodes, 91 pipes, 4 compressors (labelled 1 to 4)
  - 31 custody transfer meters at 24 locations (labelled A to X)
  - Flow nodes at B to X, pressure (slack) node at A
- Hourly SCADA flow, pressure and temperature data for February and March of 2014
- Segment serves 3 CCGT power plants



Model Validation: Real Data

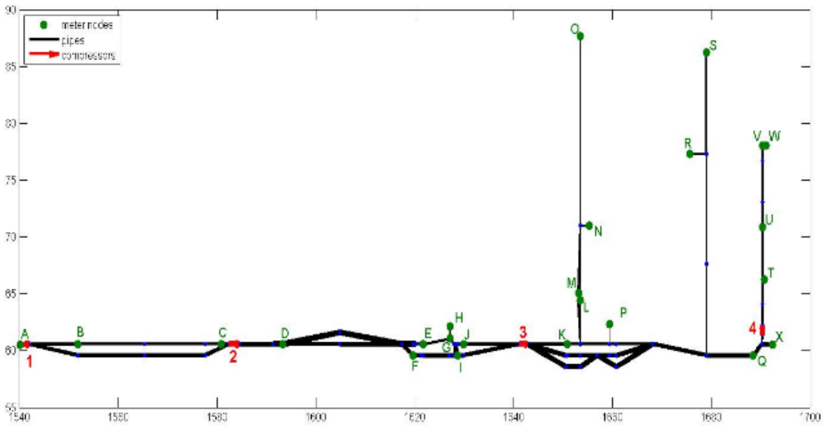
- Boundary conditions (from data):
  - Mass flow into system (injections) at flow nodes B to X
  - Pressure at slack node A

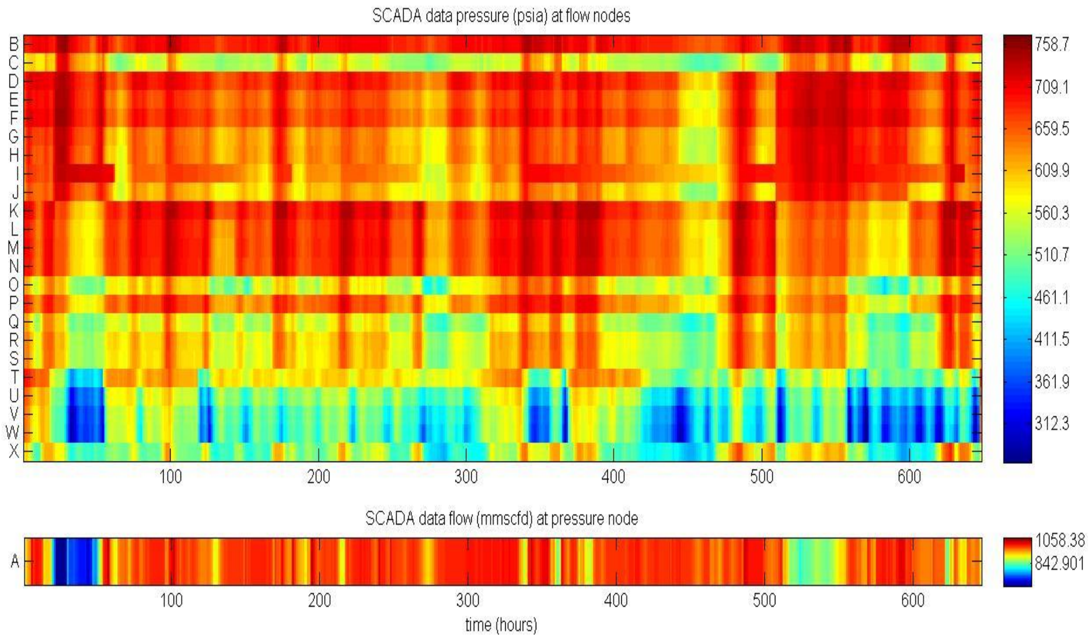


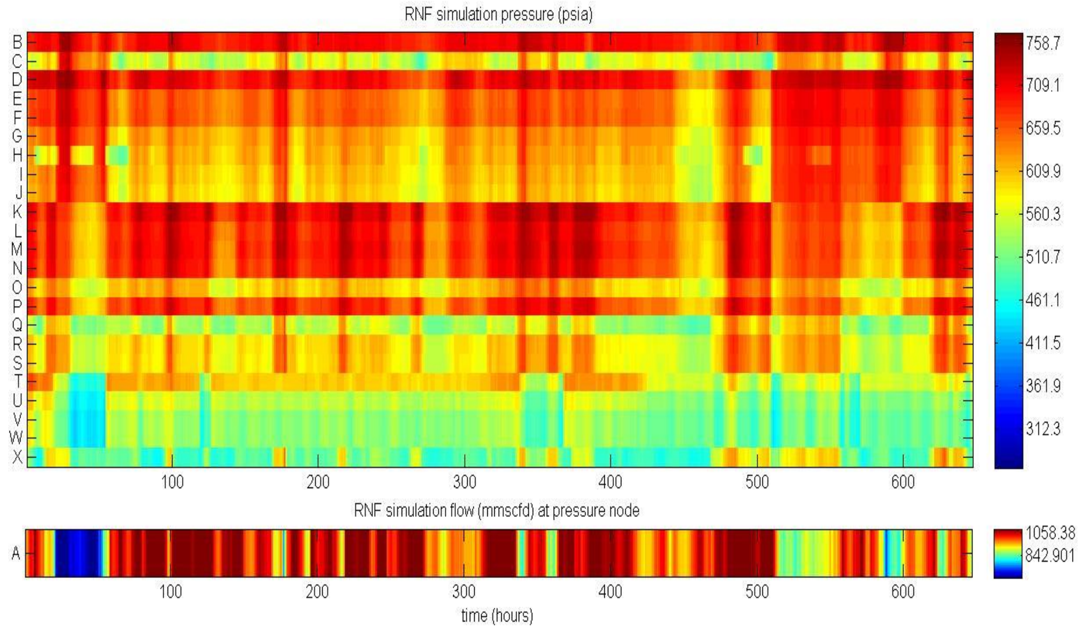


Model Validation: Real Data

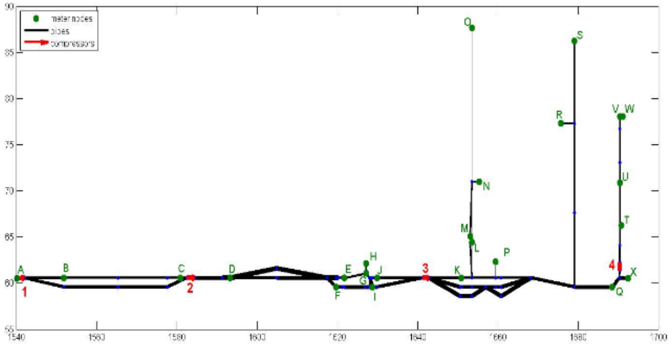
- Corresponding solution (Feb-2014 results shown)
  - Simulation using reduced model, and data
  - Pressure at flow nodes B to X
  - Mass flow into the system at slack node A



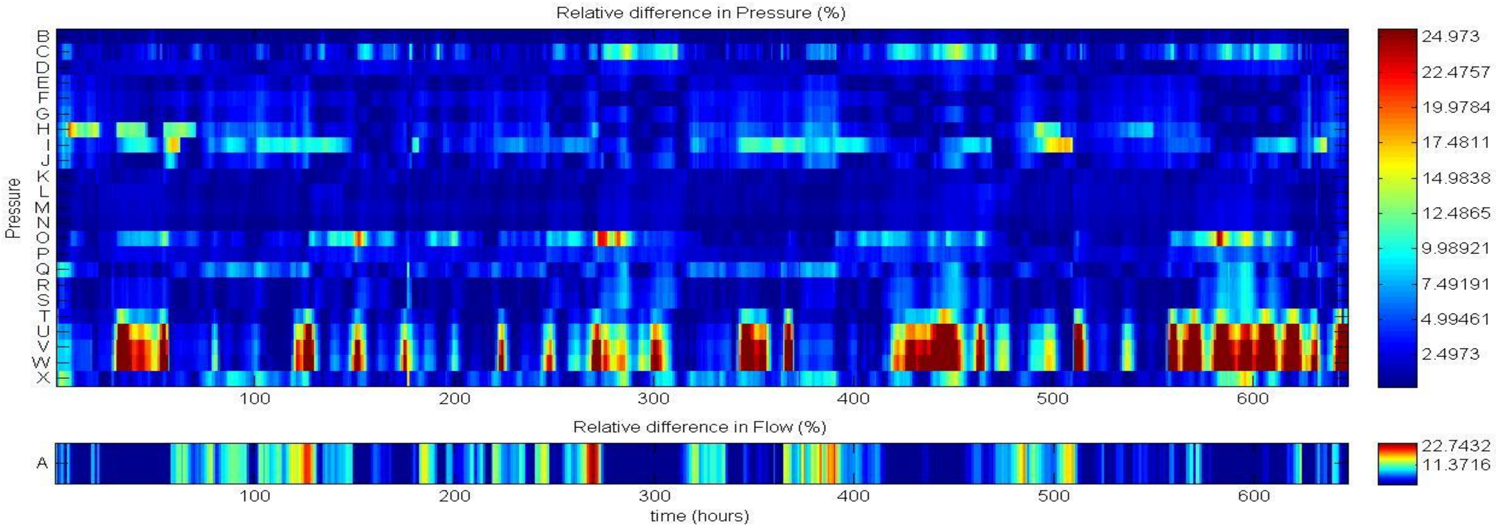




Model Validation: Deviations from Real Data



- Comparison: relative distance (%)
  - Pressure at flow nodes B to X
  - Mass flow into system at slack node A



- **Top: Flow node pressures, mean: 4.17%, (2.94% w/o U,V,W)**
- **Bottom: Flow into Pressure node A. Mean (max) 2.45% (23.7%)**

Numerical Experiments

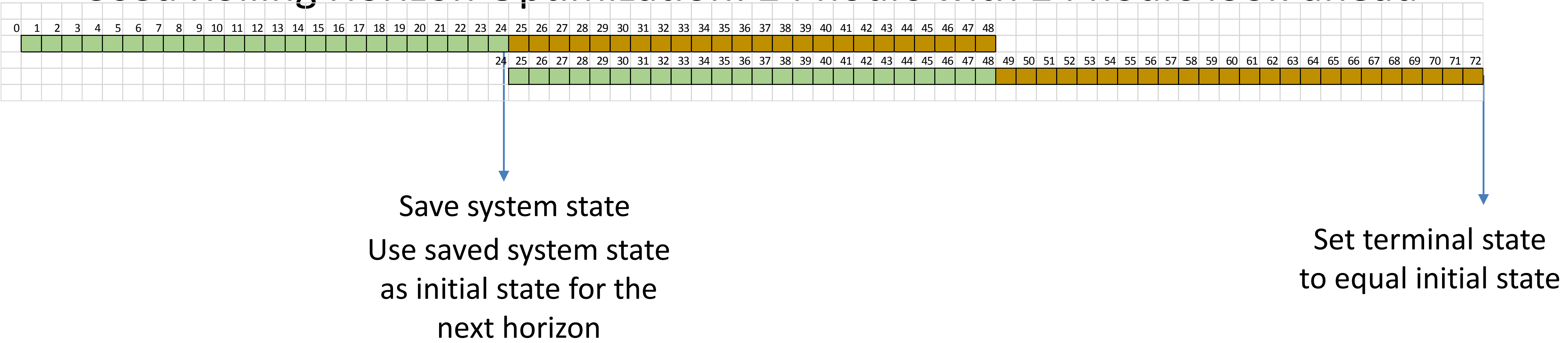
Four Optimization Experiments Conducted

Base Case	Optimized Case
Matching actual deliveries Purpose: Benchmark the model. Set up optimization to match actual deliveries and benchmark compressor operations to historical data	**Maximizing throughput** Purpose: Evaluate incremental throughput achievable via transient optimization. Compare to the Base Case
Matching actual social welfare Purpose: Set up optimization to match actual deliveries valued at historical prices and compute Locational Trade Values (LTVs) of gas based on optimization. Compare LTVs to a relevant actual price index	**Maximizing social welfare** Purpose: Evaluate incremental throughput and social welfare achievable via transient optimization. Compare to the Base Case

Results presentation

- All results are preliminary and subject to further validation and clarification
- Detailed results are shown for February 2014 only. March 2014 results are similar

- Model set-up
  - Unbounded controllable supply at upstream entry point A
  - Non-controllable supply and demand set at actual hourly levels at all points except 3 power plants and downstream exit point X
  - Controllable demand at power plants is bounded at actual hourly deliveries
  - Controllable demand at exit point X is bounded at actual delivery
  - All pressure and compressor constraints apply
  - Objective Function: maximize integral throughput (sum of deliveries)
- Used Rolling Horizon Optimization: 24 hours with 24 hours look-ahead



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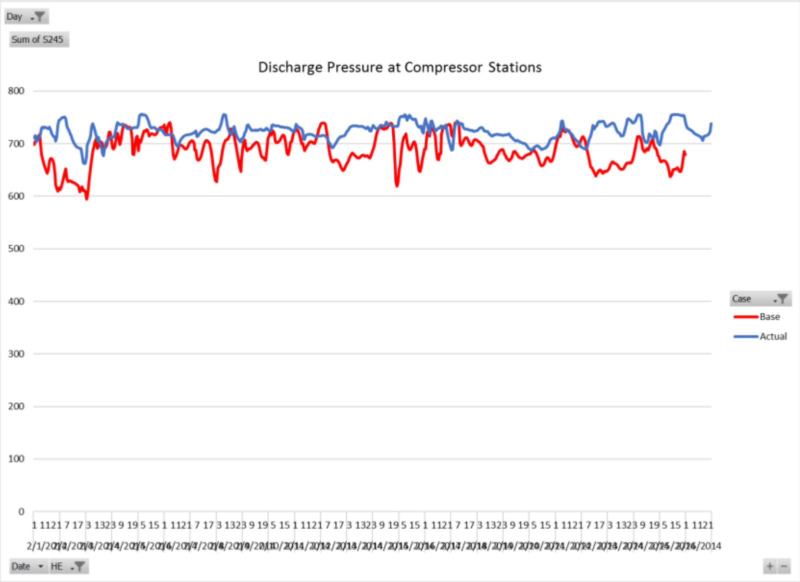
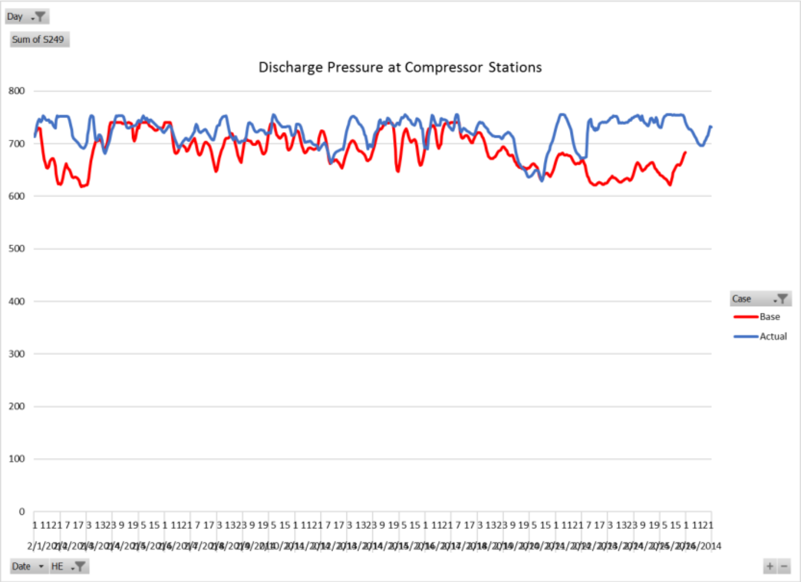
Benchmarking Compressor Settings to Actual Data: February 2014

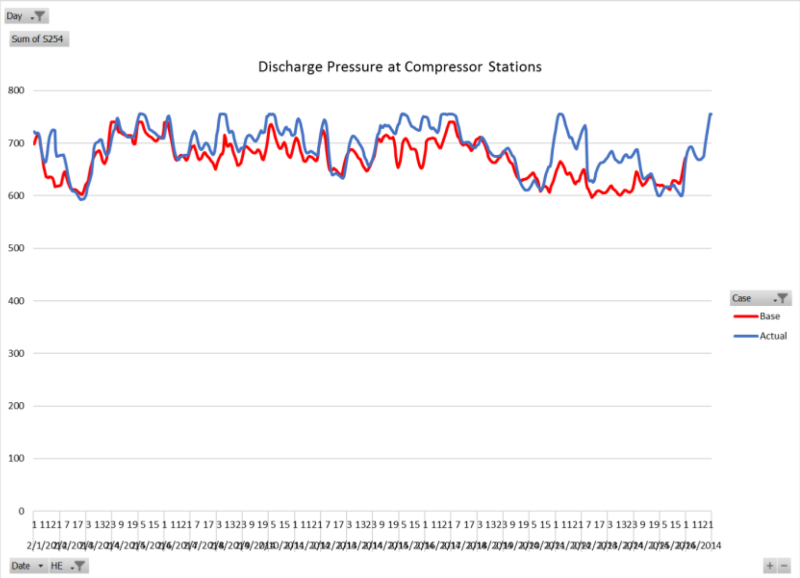


February 2014
Discharge Pressure (psia)
at Compressor Stations



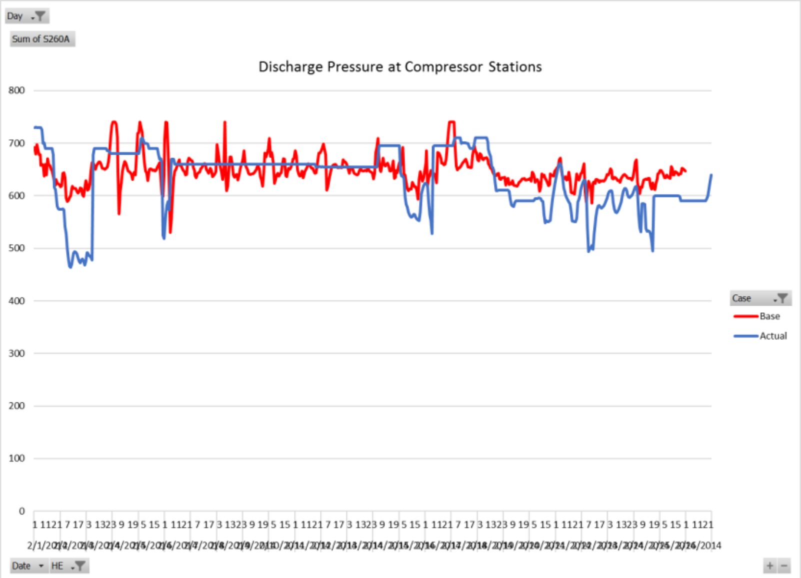
St. 1
Base Case v.
Actual

St. 2
Base Case v.
Actual



St. 3
Base Case v.
Actual

St. 4
Base Case v.
Actual



- Modeled compressor operations do not match actual data
  - Optimization model uses a number of simplifications
  - Exact limits on pressures and compressor capabilities are not known and are based on observation statistics
  - Actual operations do not follow transient optimization process
- However, compressor settings resulting from optimization simulations appear to be within a reasonable range of actual data

Throughput Maximization

- Matching actual deliveries
  - Unbounded controllable supply at upstream entry point A
  - Non-controllable supply and demand set at actual hourly levels at all points except 3 power plants and downstream exit point X
  - Controllable demand at power plants is bounded at actual hourly deliveries
  - Controllable demand at exit point X is bounded at actual delivery
  - All pressure and compressor constraints apply
  - Objective Function: maximize integral throughput (sum of deliveries)

- Maximizing Throughput
  - Unbounded controllable supply at upstream entry point A
  - Non-controllable supply and demand set at actual hourly levels at all points except 3 power plants and downstream exit point X
  - Controllable demand at power plants is bounded at actual hourly deliveries
  - Controllable demand at exit point X is unbounded
  - All pressure and compressor constraints apply
  - Objective Function: maximize integral throughput (sum of deliveries)

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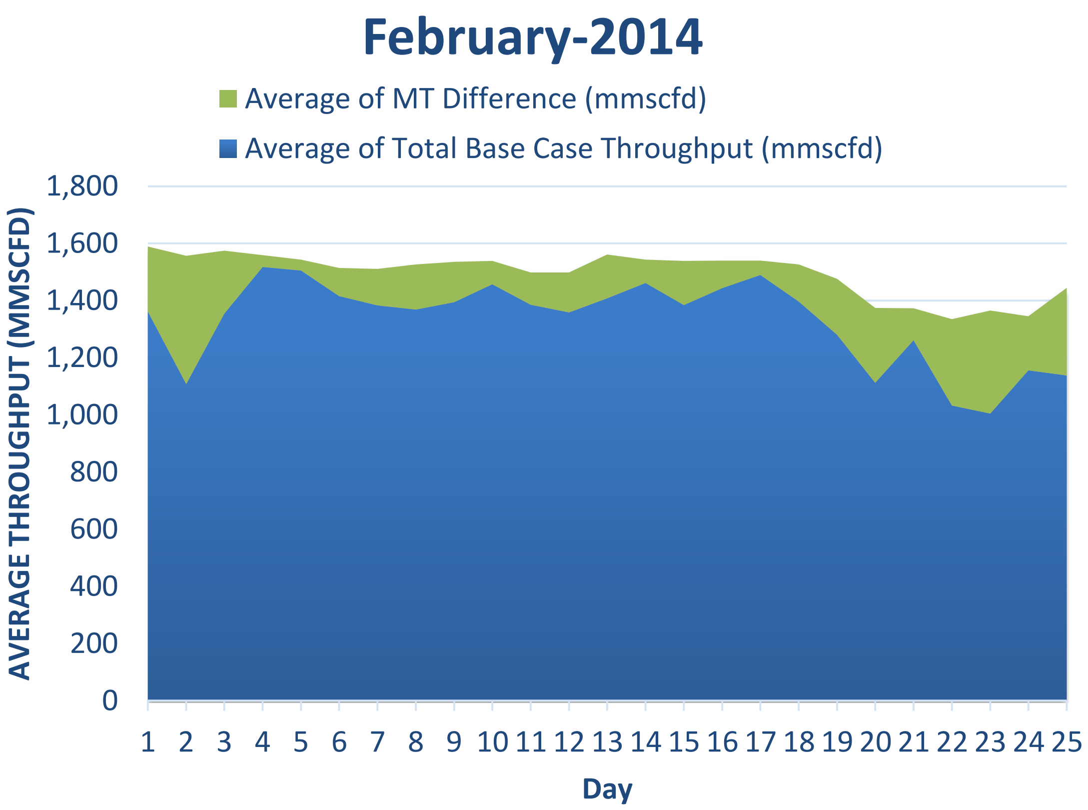
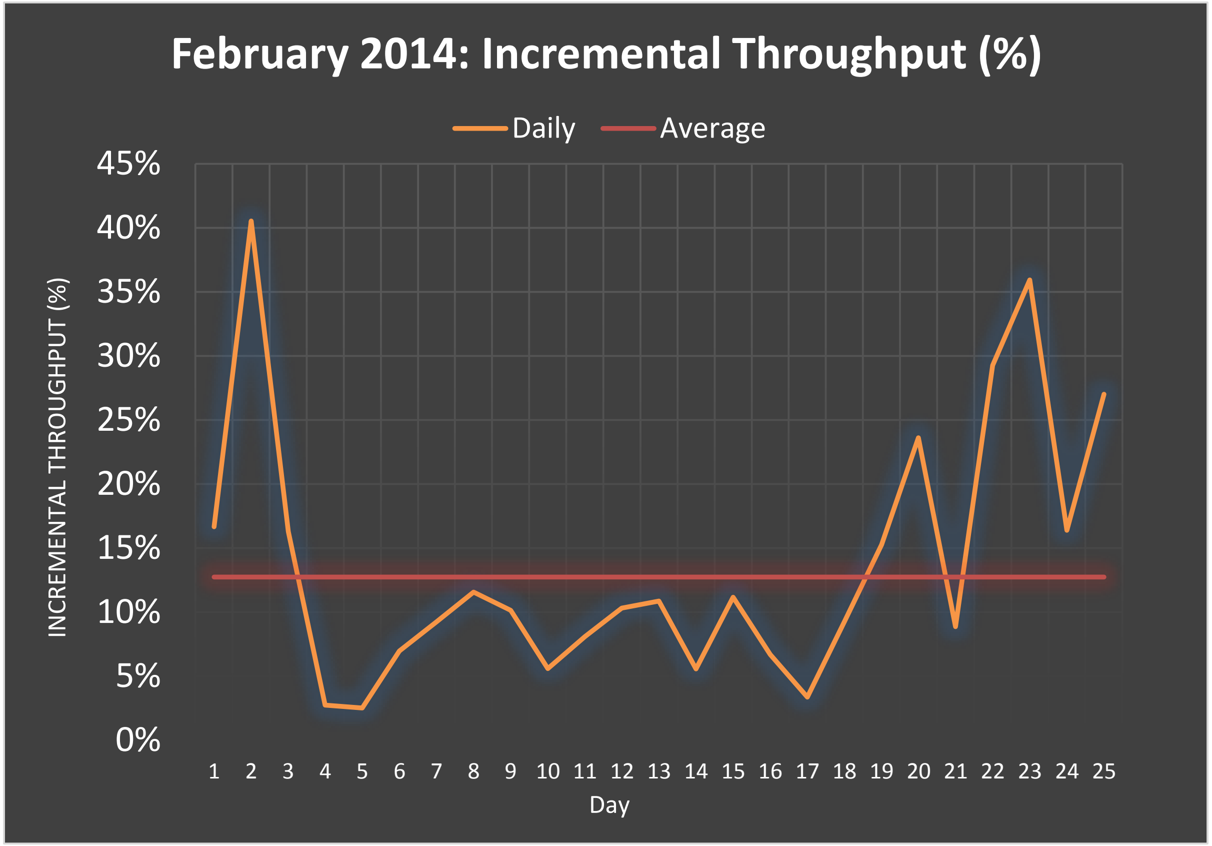
Transient throughput optimization. February–2014
Daily Results





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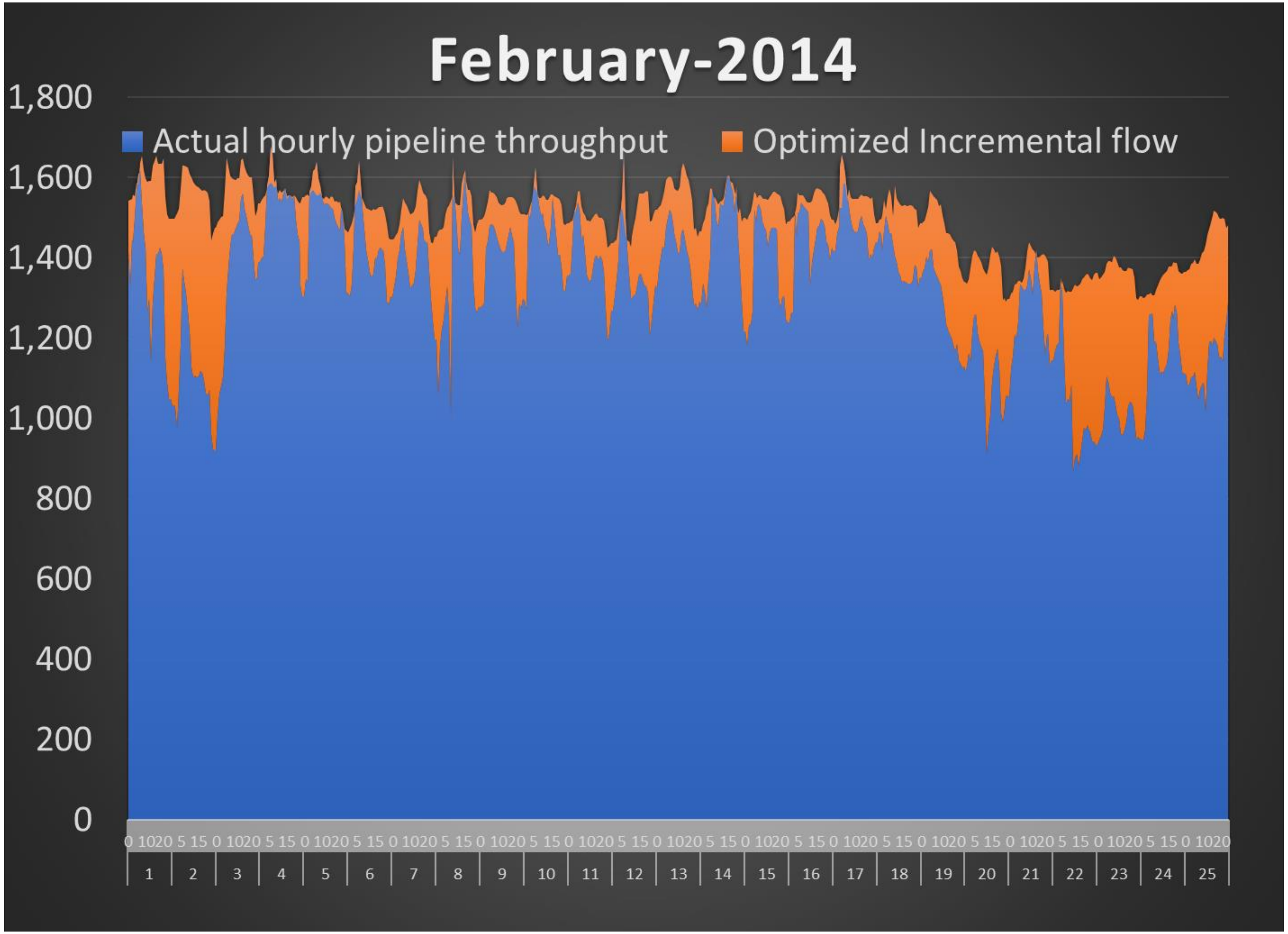
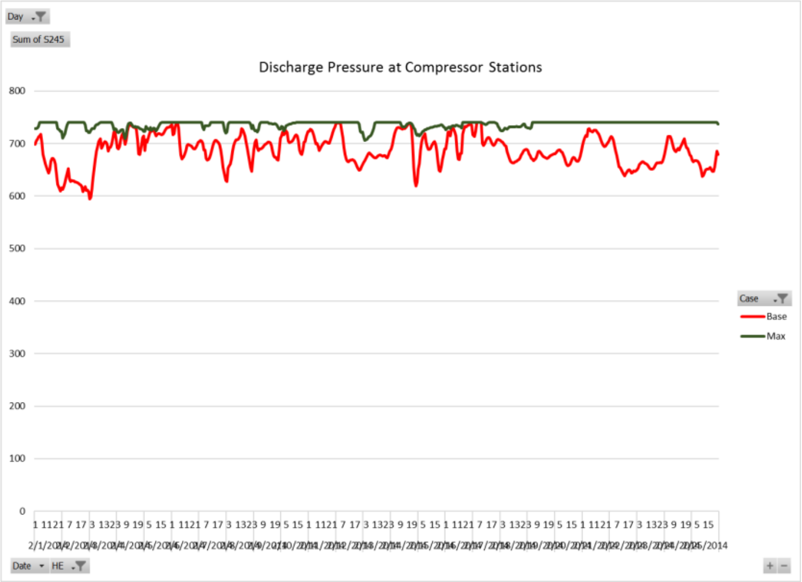
Transient throughput optimization. February–2014
Hourly Results

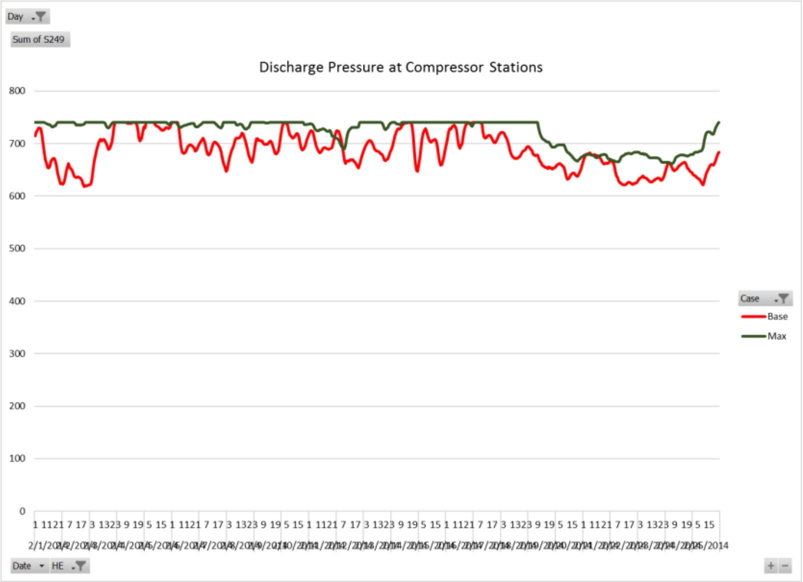


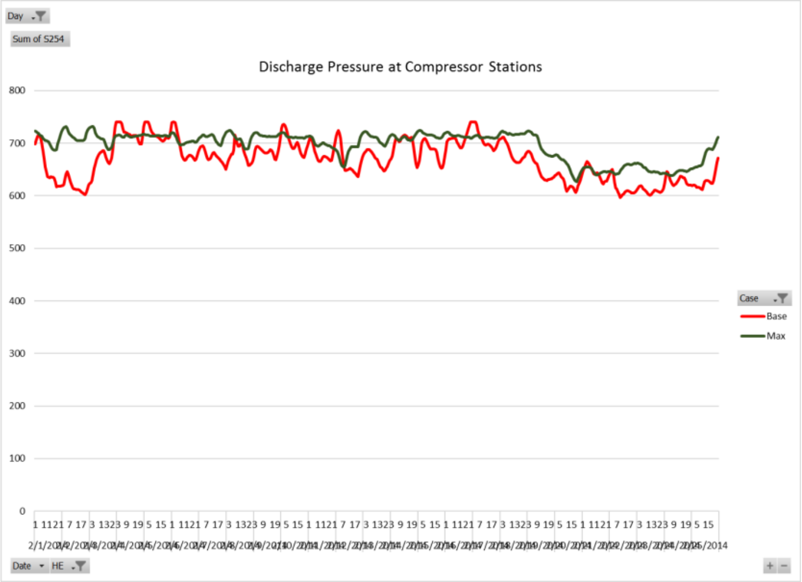
February 2014
Discharge Pressure (psia) at Compressor Stations



St. 1
Base Case v.
Max
Throughput

St. 2
Base Case v.
Max
Throughput





St. 3
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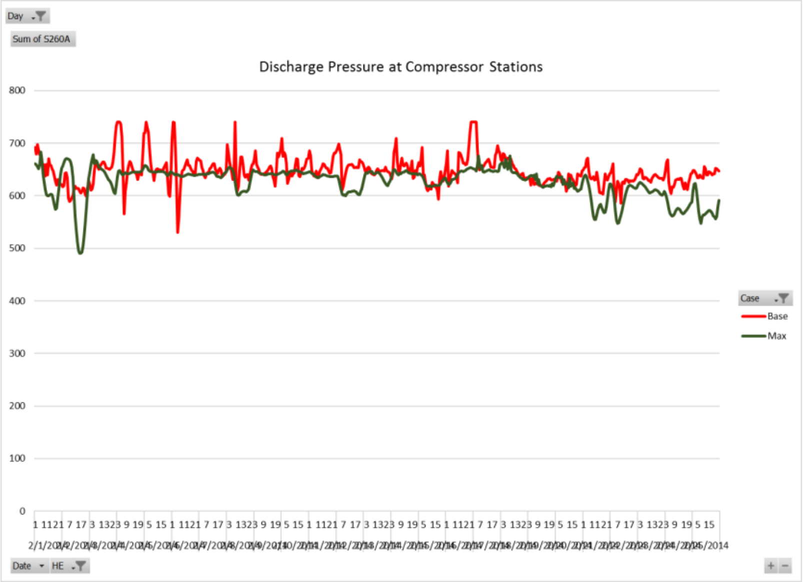

Preliminary Findings from Throughput Maximization

- Transient optimization could increase the throughput by 12% - 14 % on average during the constrained time – Polar Vortex Period of February – March 2014
- That incremental throughput is unevenly spread in time
- It is possible however that larger increase in delivery is achieved at times when pipeline was not constrained and therefore the real effect of transient optimization could be smaller
- A more relevant metric would be to assess the increase in throughput “at time of need”

Use of Historical Prices to Measure the Need

- Supply's offers are priced using daily upstream price index
- Actual demand's willingness to pay is priced at daily downstream price index for all delivery points except power plants
- Power plant's willingness to pay is priced hourly at *LMP/HeatRate* using plant specific LMPs and heat rates
- Incremental downstream demand is priced at *HubLMP/8.5* using relevant electricity market hub
- These prices are used to compute Social Welfare as a market surplus for the pipeline segment in question

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Benchmarking the Base Case to Historical Prices

- Matching actual throughput
  - Unbounded controllable supply at upstream entry point A
  - Non-controllable supply and demand set at actual hourly levels at all points except 3 power plants and downstream exit point X
  - Controllable demand at power plants is bounded at actual hourly deliveries
  - Controllable demand at exit point X is bounded at actual delivery
  - All pressure and compressor constraints apply
  - Objective Function: maximize integral throughput (sum of deliveries minus sum of supplies)

- Matching actual social welfare
  - Unbounded controllable supply at upstream entry point A
  - Non-controllable supply and demand set at actual hourly levels at all points except 3 power plants and downstream exit point X
  - Controllable demand at power plants is bounded at actual hourly deliveries
  - Controllable demand at exit point X is bounded at actual delivery
  - All pressure and compressor constraints apply
  - Objective Function: maximize integral social welfare (summed over time total market surplus between buyers and sellers)

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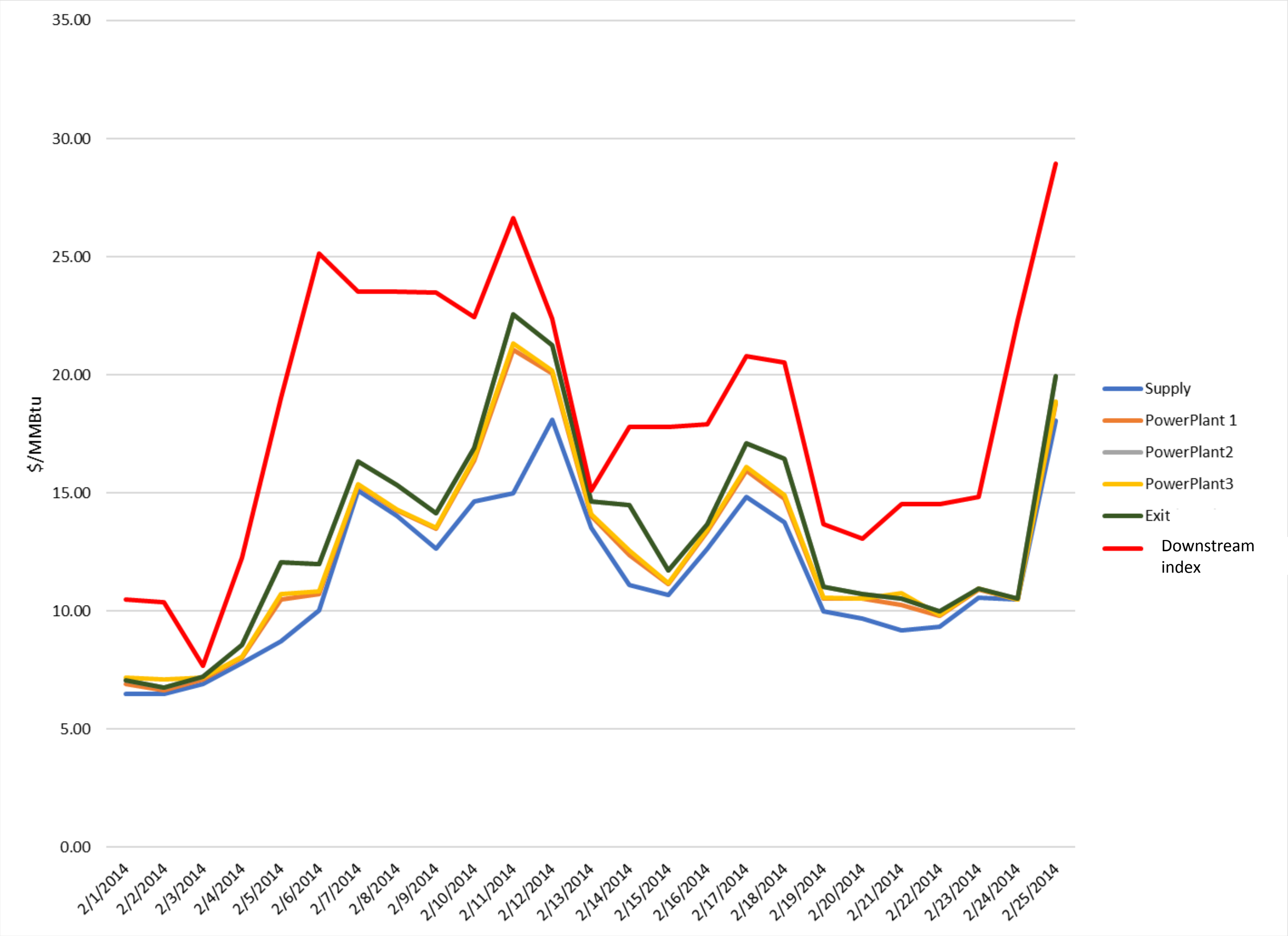
Daily LTVs compared to downstream index



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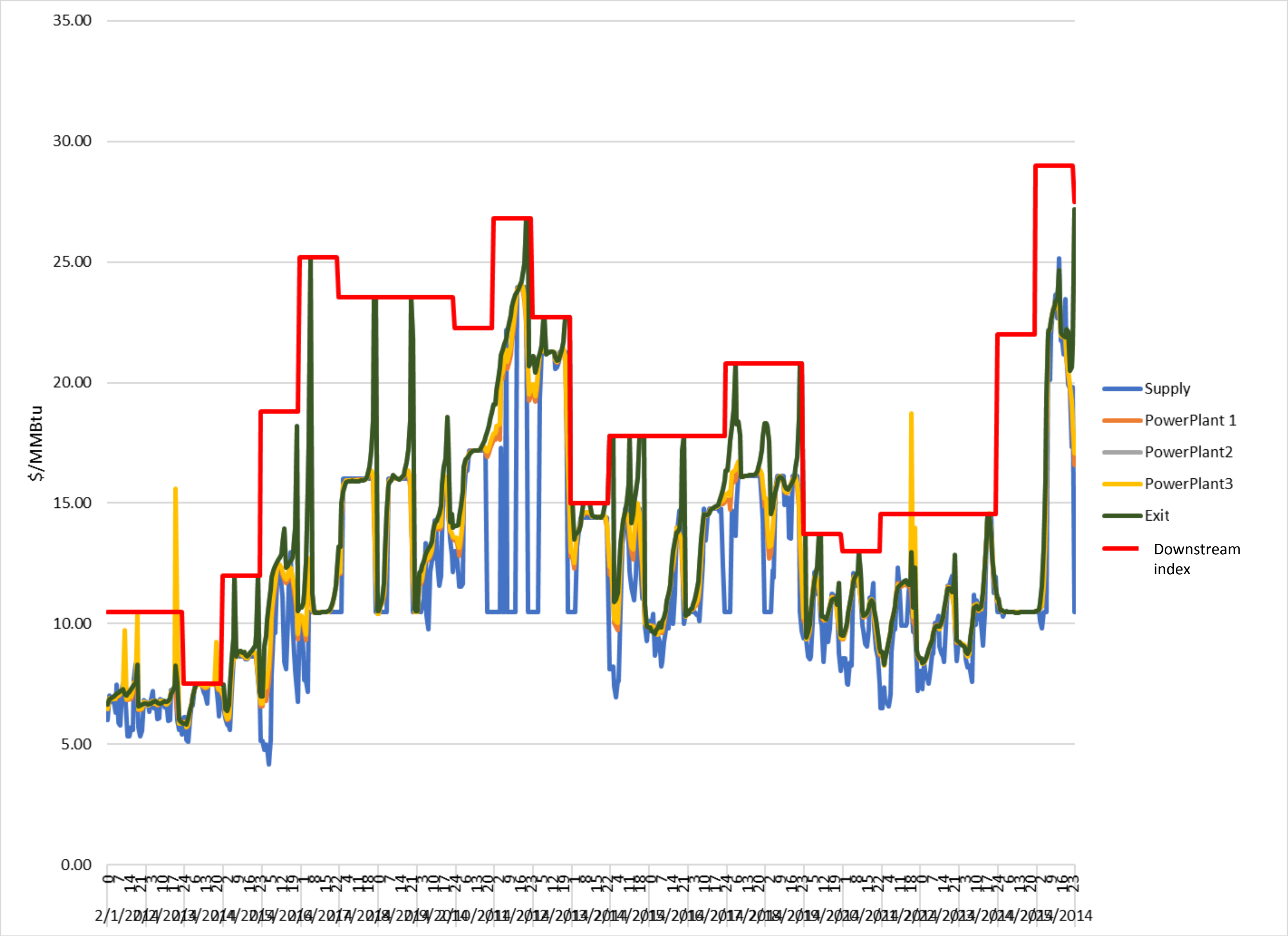
Hourly LTV comparison to daily downstream index



Maximizing Social Welfare

- Matching actual social welfare
  - Unbounded controllable supply at upstream entry point A
  - Non-controllable supply and demand set at actual hourly levels at all points except 3 power plants and downstream exit point X
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  - Objective Function: maximize integral social welfare (summed over time total market surplus between buyers and sellers)

- Maximizing social welfare
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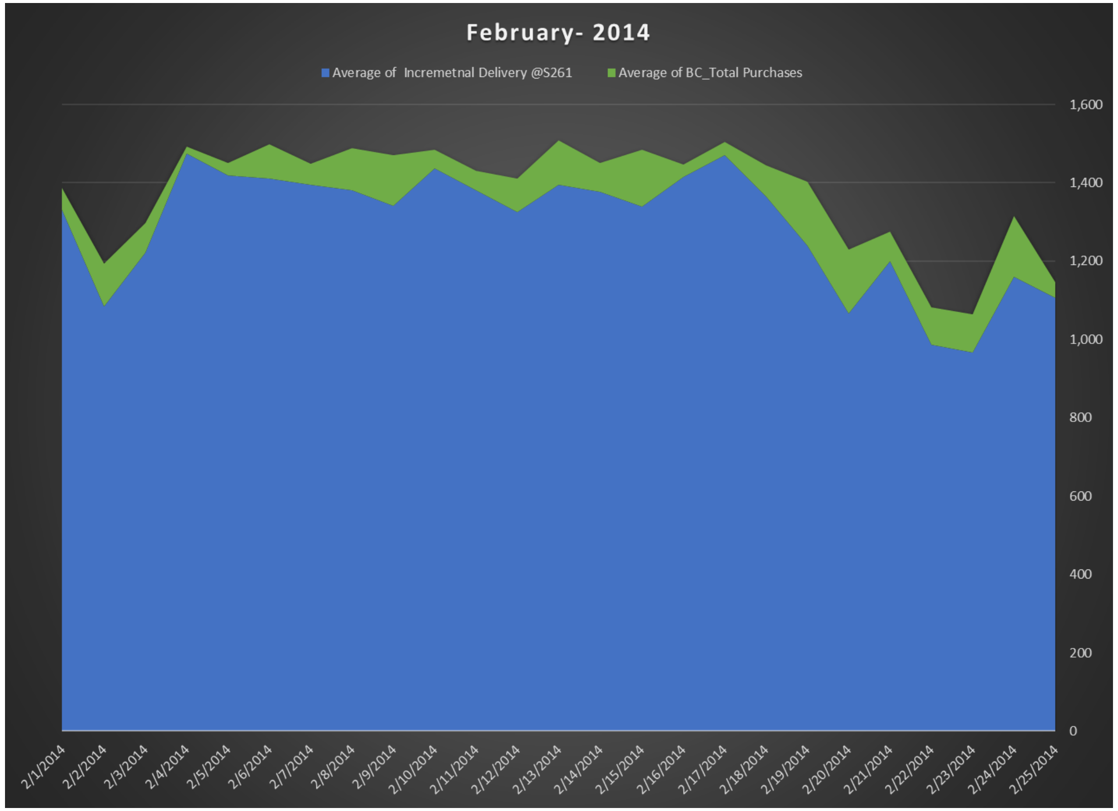
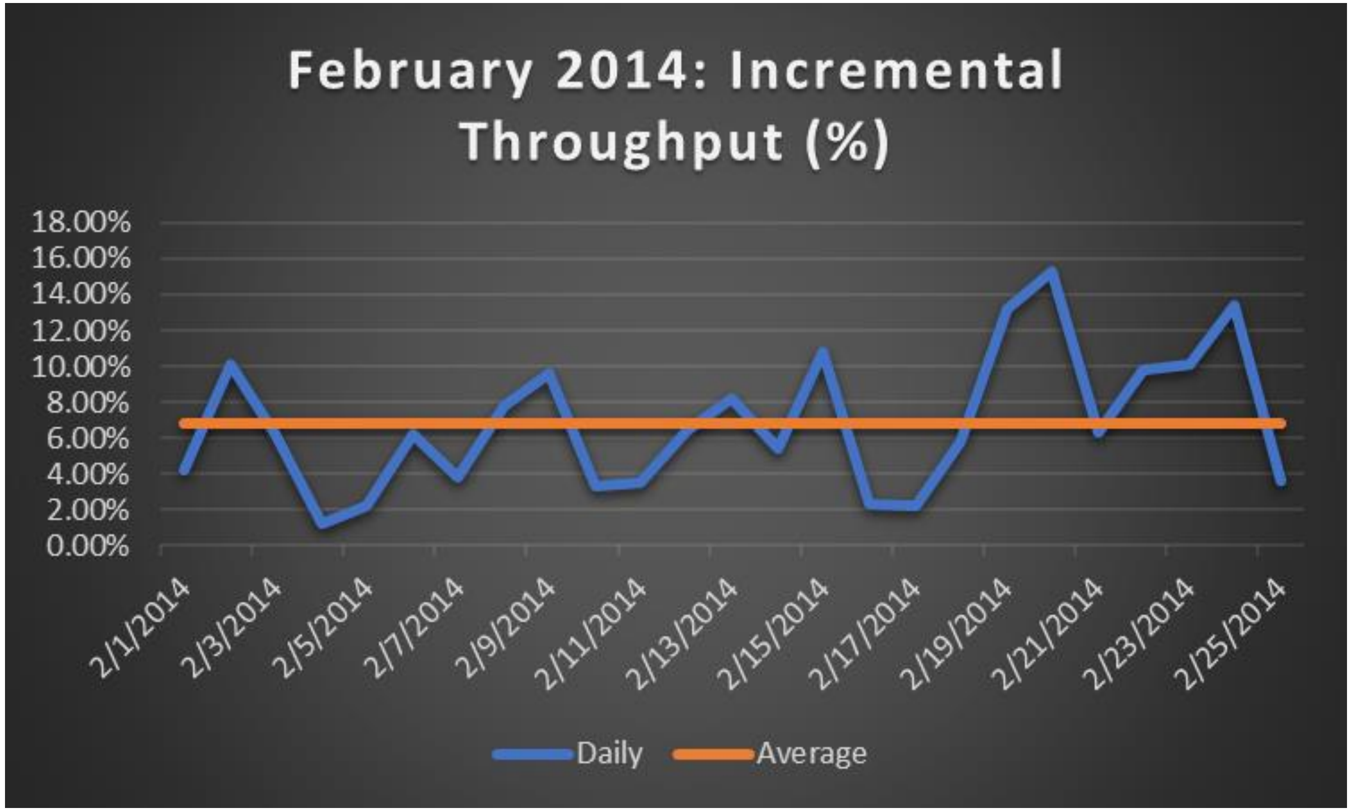
  - All pressure and compressor constraints apply
  - Objective Function: maximize integral social welfare (summed over time total market surplus between buyers and sellers)

Results: incremental throughput at time of need is approximately 7% of total throughput





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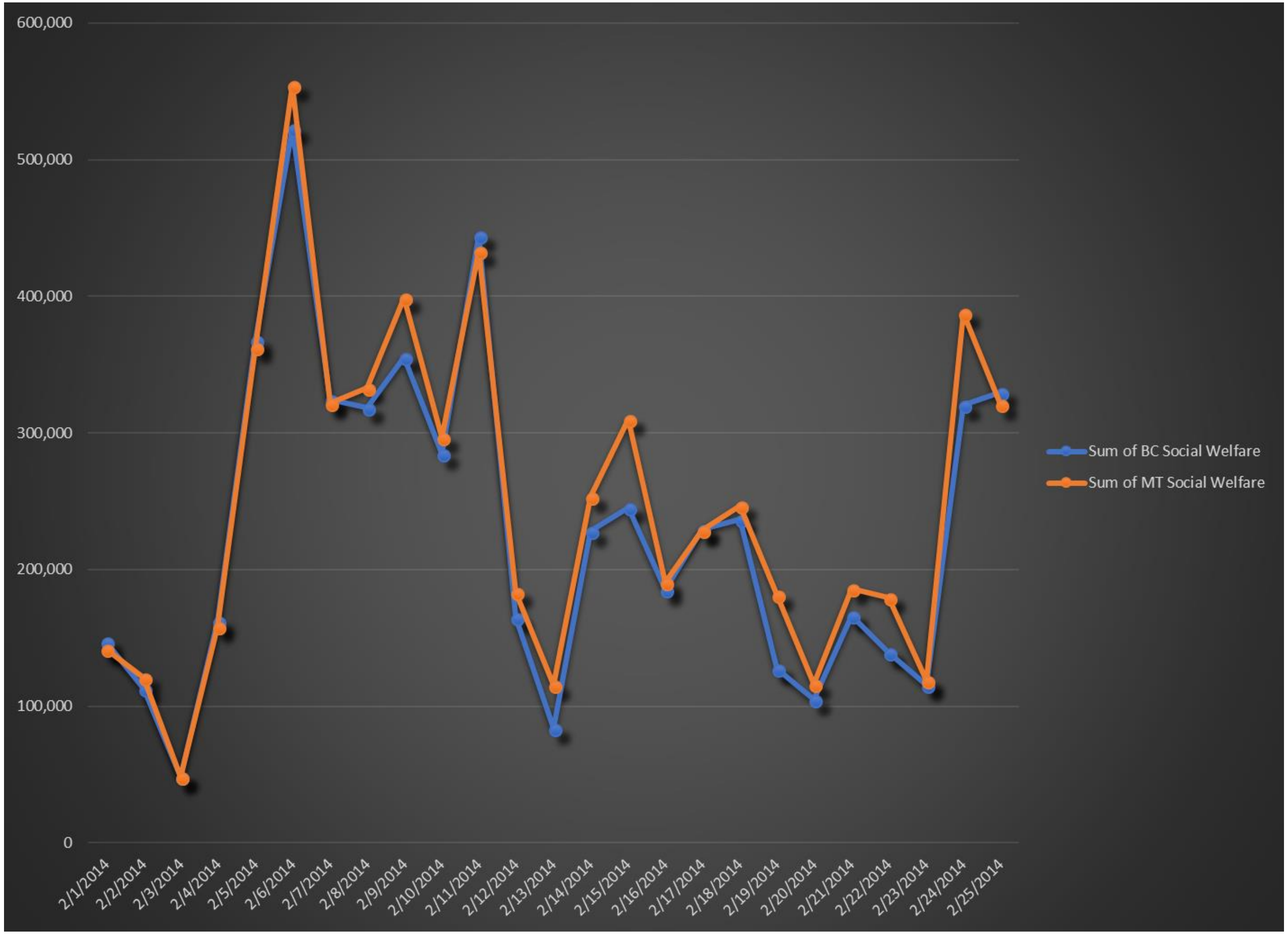
Maximized social welfare is 8% higher than in the Base Case



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Summary of Results

	February 2014	March 2014
Throughput increase		
Total potential	12%	14%
In time of need	7%	9%
Price reduction at downstream exit point	28%	14%
Increase in Social Welfare	8%	7%

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Discussion

- Transient optimization
  - produces valid results for real-size systems
  - has a potential to increase pipeline capacity under constrained conditions
- Transient optimization can support operation of the Gas Balancing Market
- Gas Balancing Market if developed
  - can improve social welfare of the gas supply system
  - can be used to improve coordination of gas and electric systems and increase social welfare of both systems (to be confirmed in forthcoming simulations)
- Provided estimates of social welfare increase are conservative as they are based on the assumption that only electric generating plants participate in the balancing market