RTO Scale Unit Commitment Test Cases

Test case data set status and preliminary results

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Overview

Origin:

- June 2010 FERC conference, discussion of large scale test problem creation

Purpose:

- Create a data set that can be used to model RTO-scale unit commitment and economic dispatch. Intended to be used to produce representative unit commitment models.
  - Not intended to simulate the exact operation of an actual RTO.
- To enable benchmarking of methods among researchers and engineers to test improvements optimization methods and demonstrate formulations
- Similar to IEEE test sets (14 bus, 73 bus, etc), but larger (> 10,000 bus) and contains more day ahead market characteristics (e.g. demand bidding, virtual bidding).

The Data Set

- Contains information to construct an approximation of an RTO day ahead unit commitment.
  - To test scheduling, dispatch and pricing optimization algorithms. Not to replicate reliability functions, mitigation functions, or other analysis.

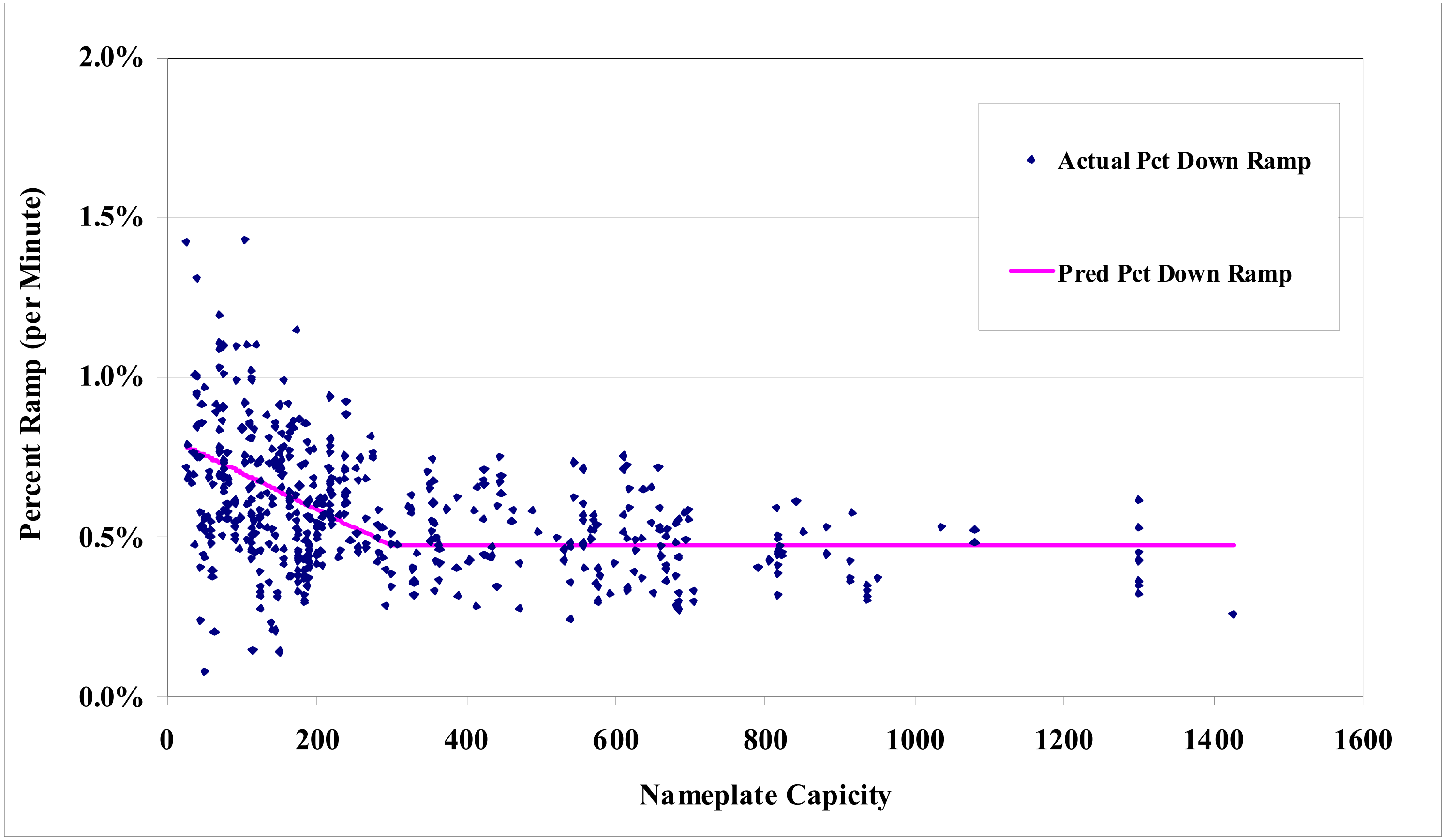
- RTO scale system
  - Network – over 10,000 buses, over 15,000 transmission elements
  - Generators - over 1,000 generating units, including wind following a profile
  - Loads – including fixed demand, price sensitive demand, demand response
  - Inc and dec bids

Data Set

- Generator data – from EIA 411, EIA 860, EPA, NREL, RTO website
- Generators offer curves estimated, created using data from publicly available sources
- Demand data – RTO website
- Network data – Obtained from an RTO
- Generator and Demand data was assembled from public information, CEII restrictions on the network model

Ramp Rates

- Ramp rate inputs were developed from statistical analysis of EPA data on units in the RTO. Ramp rates predicted as a function of the unit nameplate capacity.



- Similar analysis undertaken to predict min run level as a function of max capacity

Day Ahead Unit Commitment

- This talk discusses a model that was created to verify that the data set produces reasonable solutions

- Scenarios in the data set
  - The data set contains information for two days: Summer (Day A), Winter (Day B) both were solved
  - Each day has different demand information; variation in network and generator information

- Day ahead unit commitment (UC) - Mixed Integer Programming problem. Modeled in GAMS and solved using a leading solver.

- Model is a "first order approximation" of an RTO Day Ahead UC
  - Includes: Commitment and dispatch constraints, transmission constraints, flowgates, reserves, inc/dec bids, price responsive demand, DR, wind
  - Does not include: AC feasibility iteration, contingencies, self-schedules, losses

Day Ahead Unit Commitment – Sets and Indices

Sets and Indices

$t \in T$	Time periods (hours)	$n \in N$	Network Buses
$g \in G$	Generators	n^b_r	Market Entity to Bus Mapping
$dr \in DR$	Demand Response Resources	$k \in K$	Transmission Elements (XFMRs, Branches)
$pd \in PD$	Price Responsive Demand Bids	$int \in INT$	Interfaces
$inc \in INC$	Inc Bids	k^{int}	Subset of branches belonging to interface int
$dec \in DEC$	Dec Bids	n^f_k	Transmission Element From Bus
$r \in R$	Market Entities/Resources	n^t_k	Transmission Element To Bus
	$R = G \cup DR \cup PD \cup INC \cup DEC$	$s \in S$	Bid/Offer curve Steps

Day Ahead Unit Commitment – Variables

Variables

Q_{rst}	MW cleared for market entity *r*, step *s*, hour *t*
Q_{rt}^{tot}	Total cleared MW for market entity r, hour t
$NetInj_{nt}$	Net Injection (if positive) Withdrawal (if negative) at bus n in hour t
Qr^{+}_{gt}	Ramp up variable
Qr^{-}_{gt}	Ramp down variable
Res_{gt}	Reserves provided by generator *g*, hour *t*
V_{gt}	Startup variable for generator *g*, hour *t*
W_{gt}	Shutdown variable for generator *g*, hour *t*
U_{gt}	Commitment variable for generator *g*, hour t, $U_{gt} \in \{0,1\}$
f_{kt}	Transmission element *k* flow in hour *t*
$f^{+/-}_{kt}$	Monitored transmission element limit relaxation
$F^{+/-}_{kt}$	Flowgate limit relaxation
$s^{+/-}_{kt}$	Global power balance violation

Day Ahead Unit Commitment – Model Parameters

Parameters

F_k^{Max}	Transmission Element Long Term Thermal Rating
LIM_t^{int}	Interface Limit in period t
P_r^{Max}	Resource Maximum Cleared Quantity
P_r^{Min}	Resource Minimum Cleared Quantity
NL_g	No-Load Cost for generators
UT_g	Min Run Time for generators
DT_g	Min Down Time for generators
$R_g^{Max,up}$	Max ramp-up rate for generators
$R_g^{Max,dn}$	Max ramp-down rate for generators
MW_{rs}	MW quantity Bid/Offer for resource *r* step *s*
C_{rs}	Cost Bid/Offer for resource *r* step *s*

Day Ahead Unit Commitment – Model Parameters

INJ_{nt}^{Loop}	Uncompensated Loop flow injections at bus *n* (negative if withdrawal), hour *t*
INJ_{nt}^{Tie}	Tie Schedule Injections at bus *n* (negative if withdrawal), hour *t*
INJ_{nt}^{Wind}	Wind power day ahead forecast at bus *n*, hour *t*
DEM_{nt}^{Fix}	Day ahead fixed demand at bus *n*, hour *t*
$DEM_{nt}^{Forecast}$	Day ahead forecast demand at bus *n*, hour *t*
SF_{nk}	Shift factor for injection at bus *n* on element *k* relative to a withdrawal at the slack bus
d_r	Indicates whether a market entity cleared MW is an injection or withdrawal: 1 for injection, -1 for withdrawal
Pen^{branch}	Limit relaxation penalty for transmission elements
$Pen^{flowgate}$	Limit relaxation penalty for interface
$Pen^{balance}$	Constraint violation penalty for system power balance

Day Ahead Unit Commitment - Formulation

- The Objective Function

Minimize:

(Start Up Costs) +(No Load Costs) + (Generator Energy Dispatch Costs) + (Demand Response Costs) + (Virtual Supply Costs) + (Constraint Violation Penalty Costs) -(Price Sensitive Demand Value) - (Virtual Demand Value)

Minimize

$$z =$$

$$\sum_r \sum_s \sum_t C_{rs} Q_{rst} d_r + \sum_g \sum_t (V_{gt} SU_g + U_{gt} NL_g)$$

$$+ \sum_k \sum_t Pen^{branch} (f^+_{kt} + f^-_{kt}) + \sum_i \sum_t Pen^{flowgate} (F^+_{kt} + F^-_{kt})$$

$$+ \sum_t Pen^{balance} (s^+_t + s^-_t)$$

Day Ahead Unit Commitment - Formulation

- Power Balance and Network Constraints

Dual variable

(system power balance)

$\sum_r Q_{rt}^{tot} d_r = \sum_n DEM_{nt}^{fix} - \sum_n (INJ_{nt}^{Tie} + INJ_{nt}^{Loop}) + (s_t^+ + s_t^-)$ $\quad \forall t \quad \lambda_t$

(net injection/withdrawal at bus)

$\sum_{\{r|n^b r = n\}} Q_{rt}^{tot} d_r - NetInj_{nt} = DEM_{nt}^{fix} - (INJ_{nt}^{Tie} + INJ_{nt}^{Loop})$ $\quad \forall n,t$

(thermal transmission constraints)

$f_{kt} - \sum_n NetInj_{nt} SF_{nk} = 0$

$-F_k^{max} \le f_{kt} - f_{kt}^+ + f_{kt}^- \le F_k^{max}$ $\quad \forall k,t \quad \mu^-_{kt}, \mu^+_{kt}$

Note that this formulation is *lossless*

Day Ahead Unit Commitment - Formulation

- Commitment Constraints

(startup and shutdown constraints)

$$V_{gt} - W_{gt} - U_{gt} + U_{g,t-1} = 0 \qquad \forall \text{ g,t}$$

(minimum run time for generators)

$$-\sum_{t'=t}^{t+UT_g-1} \frac{U_{gt'}}{UT_g} + V_{gt} \leq 0 \qquad \forall \text{ t}$$

(minimum down time for generators)

$$-\sum_{t'=t}^{t+DT_g-1} \frac{U_{gt'}}{DT_g} + W_{gt} \leq 0 \qquad \forall \text{ t}$$

Day Ahead Unit Commitment - Formulation

(offer curve constraints)

$$Q_{rt}^{tot} - \sum_{s} Q_{rst} = 0 \qquad \forall\ r,t$$

$$Q_{rst} \leq MW_{rs} \qquad \forall\ r,s,t$$

(generator max capability and minimum run level)

$$Q_{rt}^{tot} + Res_{gt} - P_g^{max} * U_{gt} \leq 0 \qquad \forall\ g,t$$

$$Q_{rt}^{tot} - P_g^{min} * U_{gt} \geq 0 \qquad \forall\ g,t$$

(ramp rate constraints)

$$Q_{gt}^{tot} - Q_{gt-1}^{tot} - Qr^{+}_{gt} \leq 0 \qquad \forall\ g,t$$

$$Qr^{+}_{gt} - 60 * U_{gt-1} * R_g^{max,up} - P_g^{max} V_{gt} \leq 0 \qquad \forall\ g,t$$

$$Q_{gt-1}^{tot} - Q_{gt}^{tot} - Qr^{-}_{gt} \leq 0 \qquad \forall\ g,t$$

$$Qr^{-}_{gt} - 60 * U_{gt-1} * R_g^{max,dn} - P_g^{max} W_{gt} \leq 0 \qquad \forall\ g,t$$

Day Ahead Unit Commitment - Formulation

(reserve constraints)

$\sum_g Res_{gt} + \sum_{g \in \{OfflineSupp\}} P_g^{max} * (1 - U_{gt}) \geq SysRes_t \qquad \forall\ t$

$\sum_{\mathbf{g}} Res_{gt} \geq 0.5 * SysRes_t \qquad \forall\ t$

(non-negativity, binary constraints)

$Q_{gt}^{tot}, Q_{rst}, Qr^{-}_{gt}, Qr^{+}_{gt}, Res_{gt} \geq 0$

$U_{gt}\ V_{gt}\ W_{gt} \in \{0,1\}$

Solution Time

Solution Time Summary (minutes)	Summer	Winter
Presolve	13.3	11.4
Root Node Linear Program	11.4	11.4
Branch and Bound	13.4	7.6
Nodes Explored	0 (root)	0 (root)
Final Solve (presolve + LP)	20.3	20.8

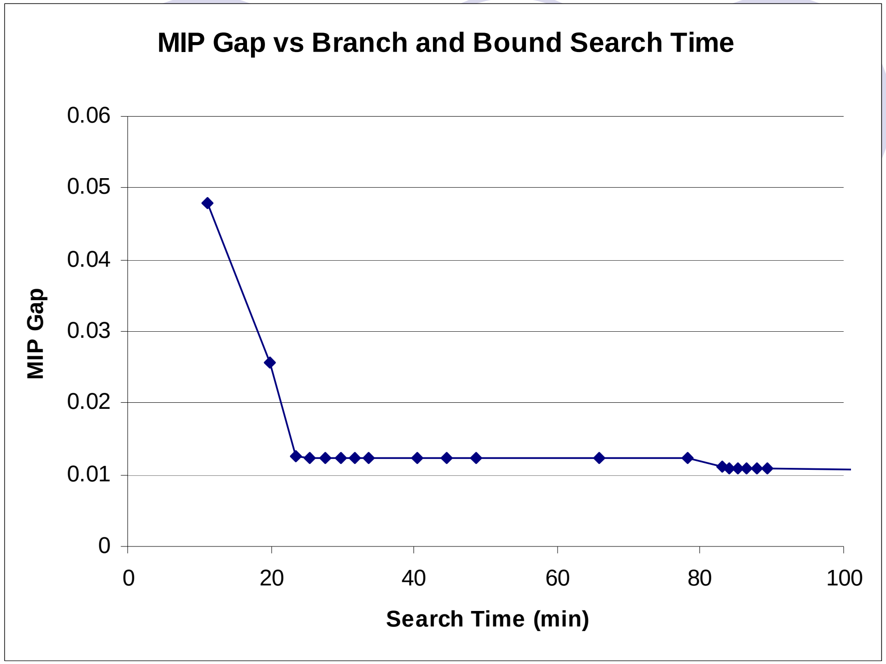
Things that could speed this up?

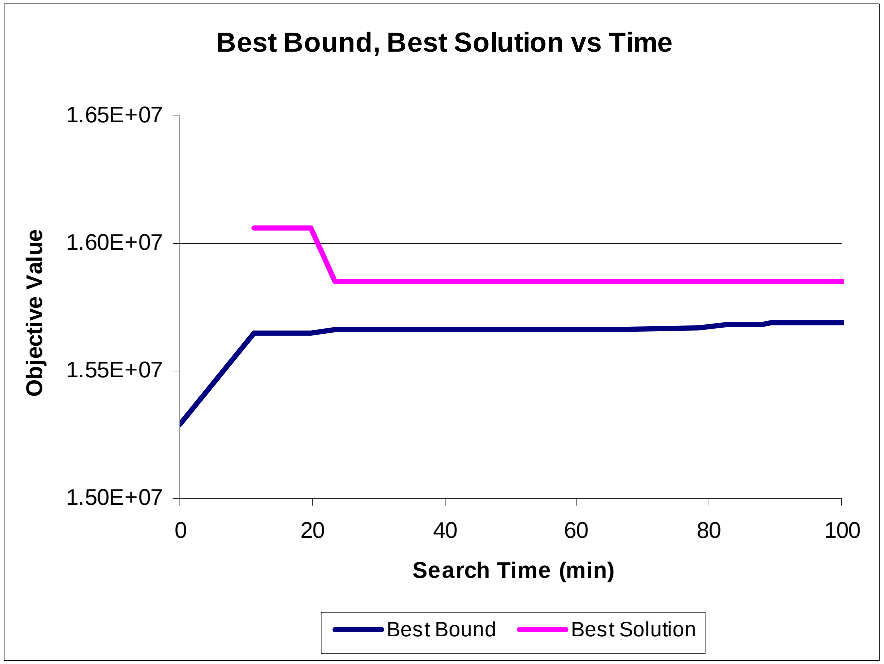
- Better formulation of the problem; experiment with solvers and settings
- Starting point

Machine: Virtual machine with 4x 2.40 GHz CPUs and 64 GB RAM

Solution Time

- MIP - After the root node LP is solved, the branch and bound search for an integer solution
  - Previously slide shows time to solution within 5% of best possible
  - Allowing the algorithm to continue, charts show solution improvement with time (for Day A)
  - After about 20 minutes, a solution with around 1% optimality gap was found, not proven optimal after 100 minutes (1% ~$150,000 gap)



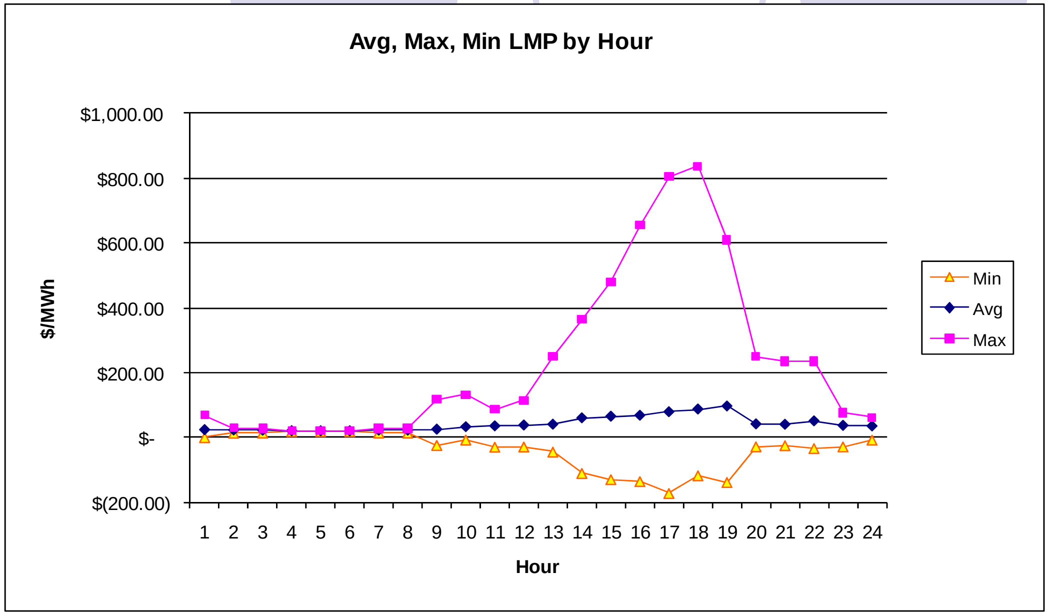


Day Ahead LMPs

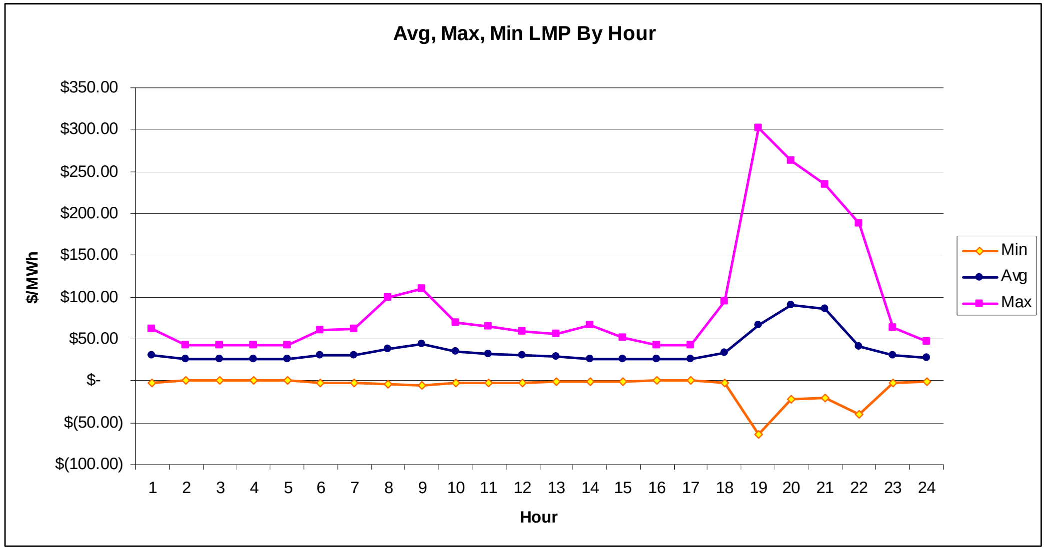
- Max, Min and Average Day Ahead LMP

across all buses by Hour

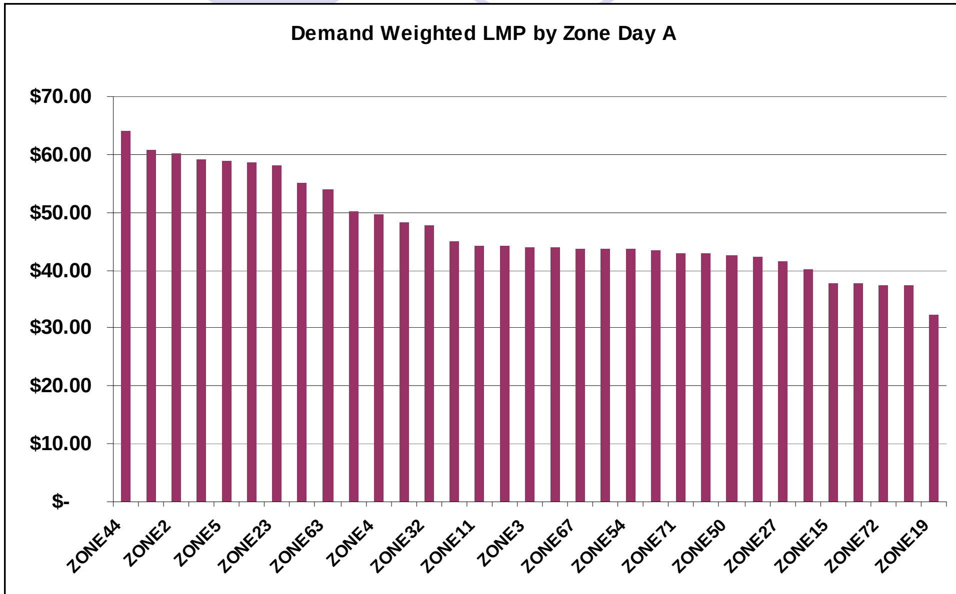
  - Day A:
  - Max LMP $804.20 at Bus 1648
  - Min LMP $(171.40) at Bus 1506

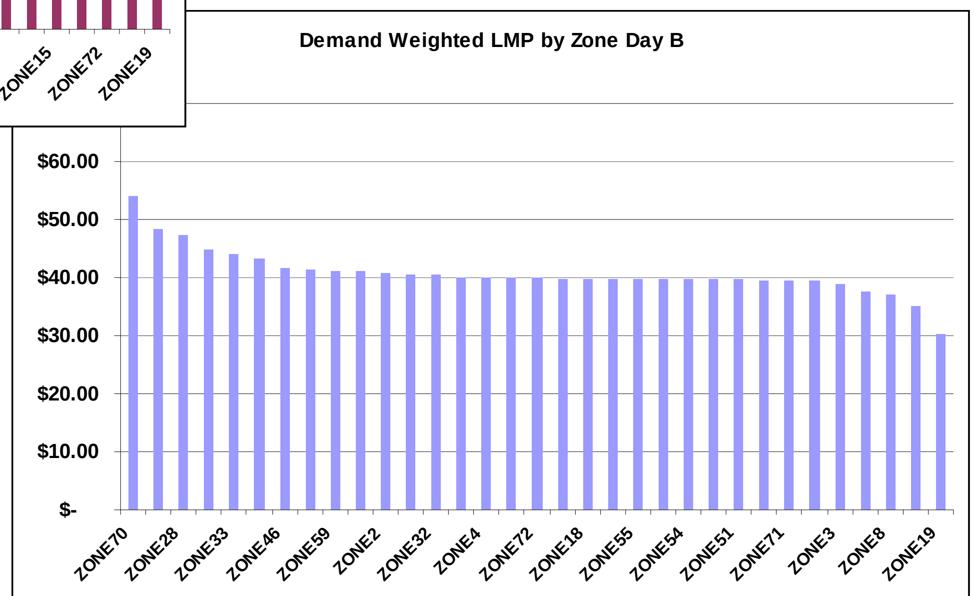


  - Day B:
  - Max LMP $301.82 at Bus 1021
  - Min LMP $(64.59) at Bus 1051

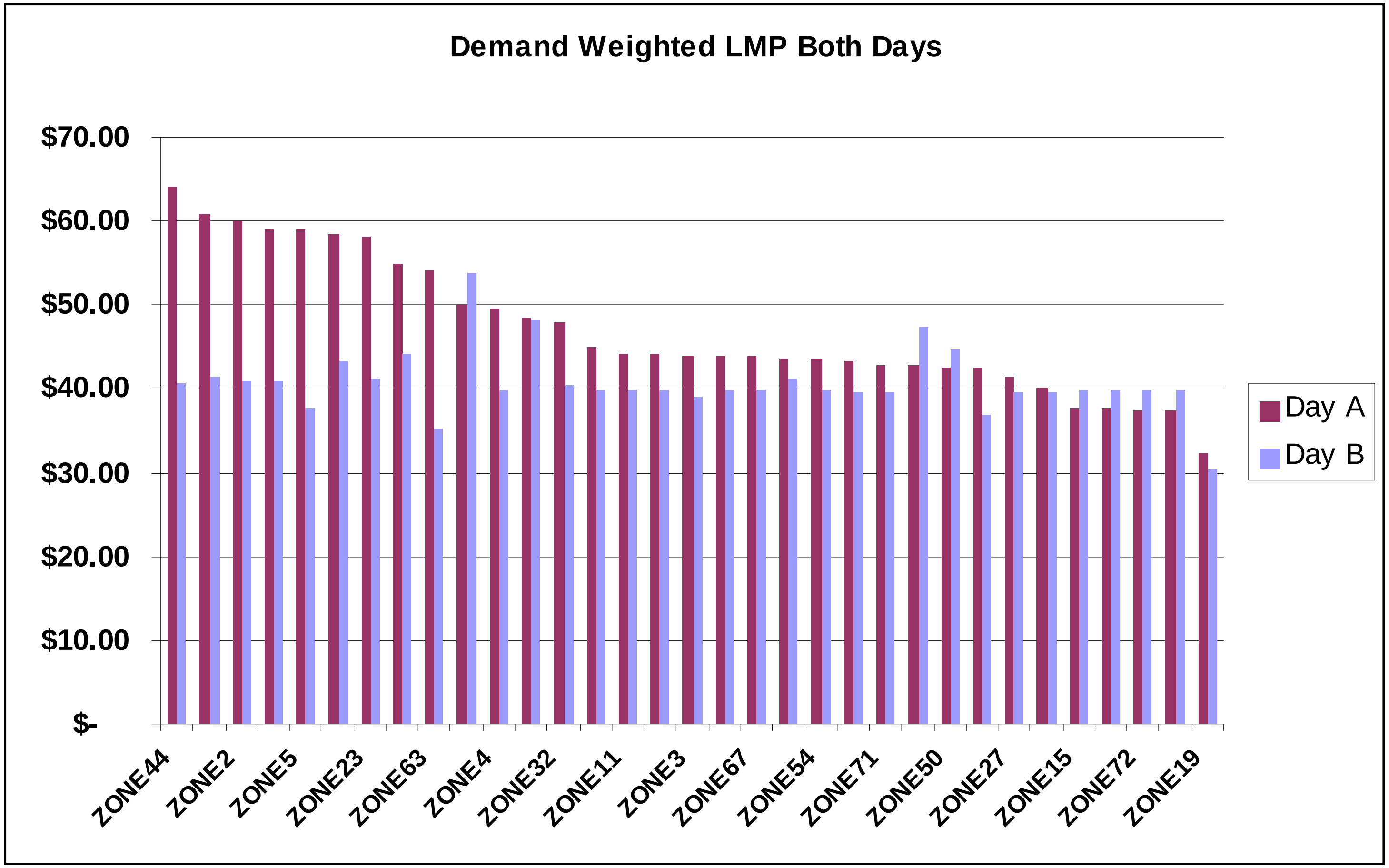


Day Ahead LMPs by Zone



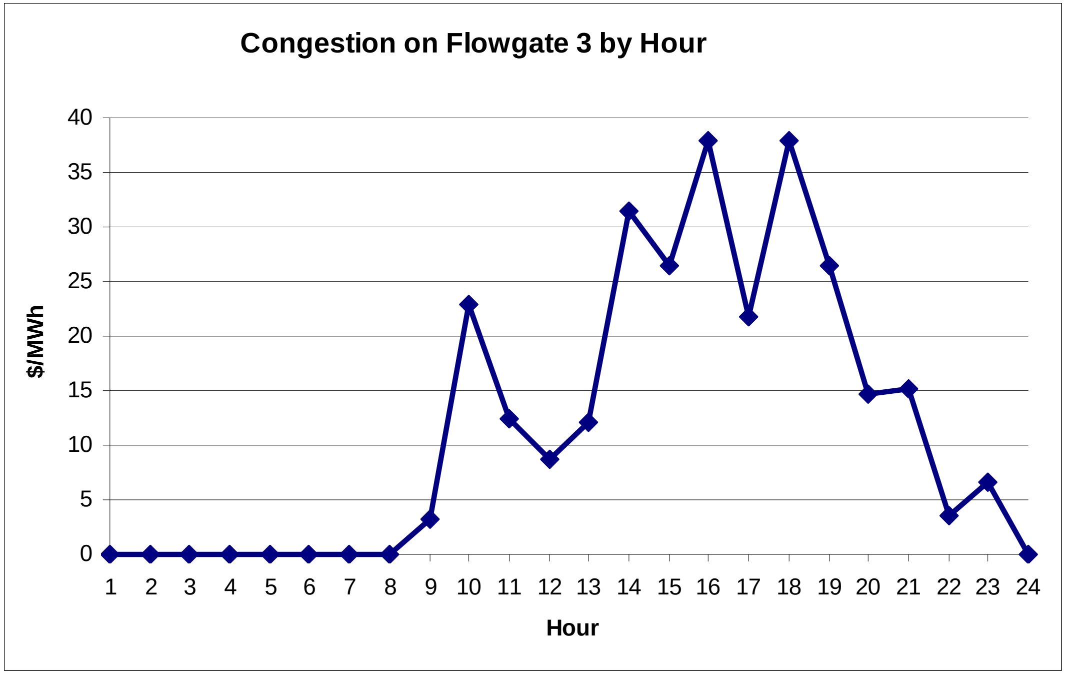


Day Ahead LMPs By Zone



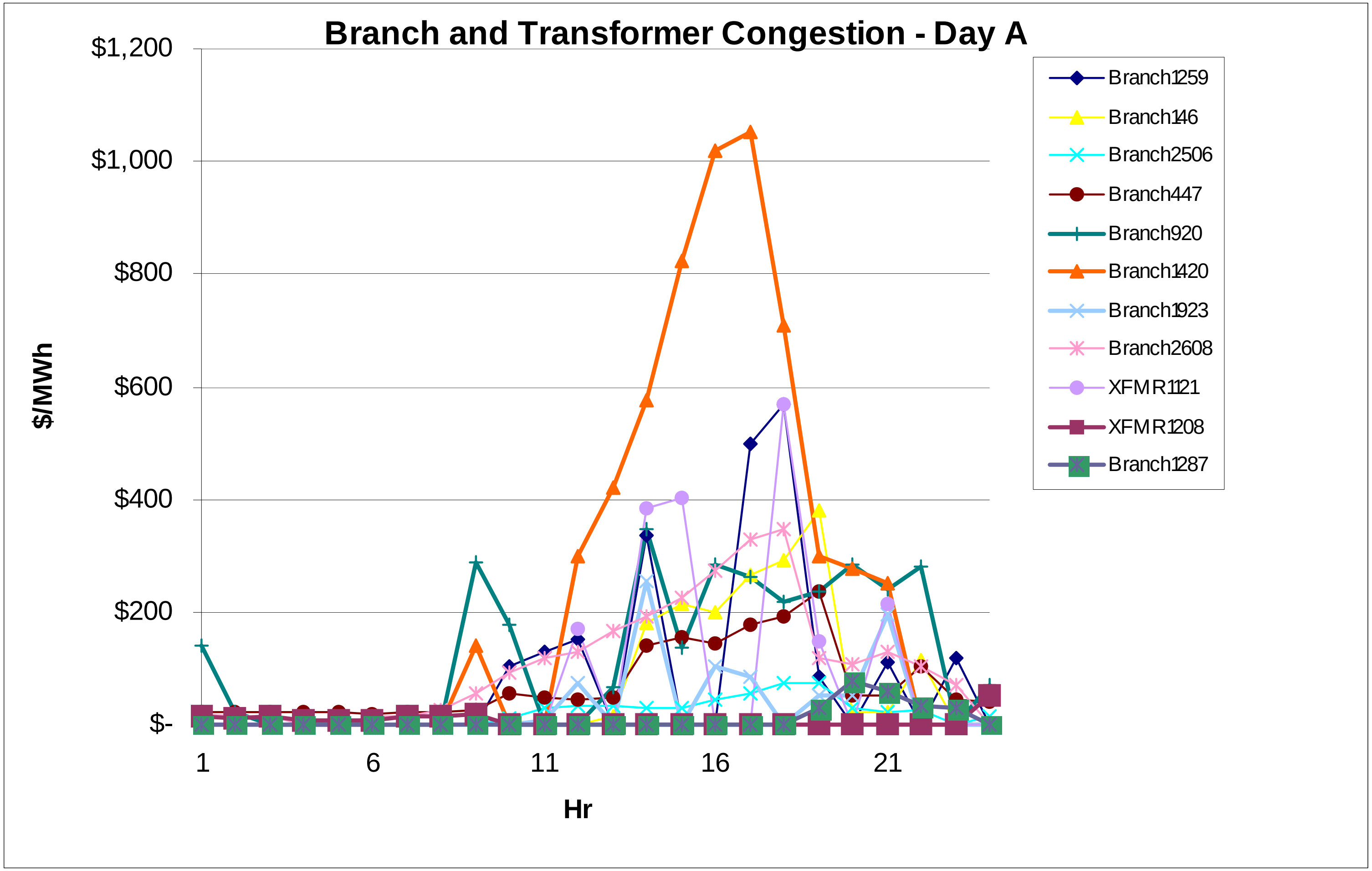
Congestion in the Day Ahead solution

- The data set contains 5 flowgates (interfaces). In the model, these were monitored in addition to over 4,000 individual transmission elements, for congestion.
- Day A: Day ahead congestion on flowgate 3.
- No flowgates were congested in Day B, at day ahead demand levels.

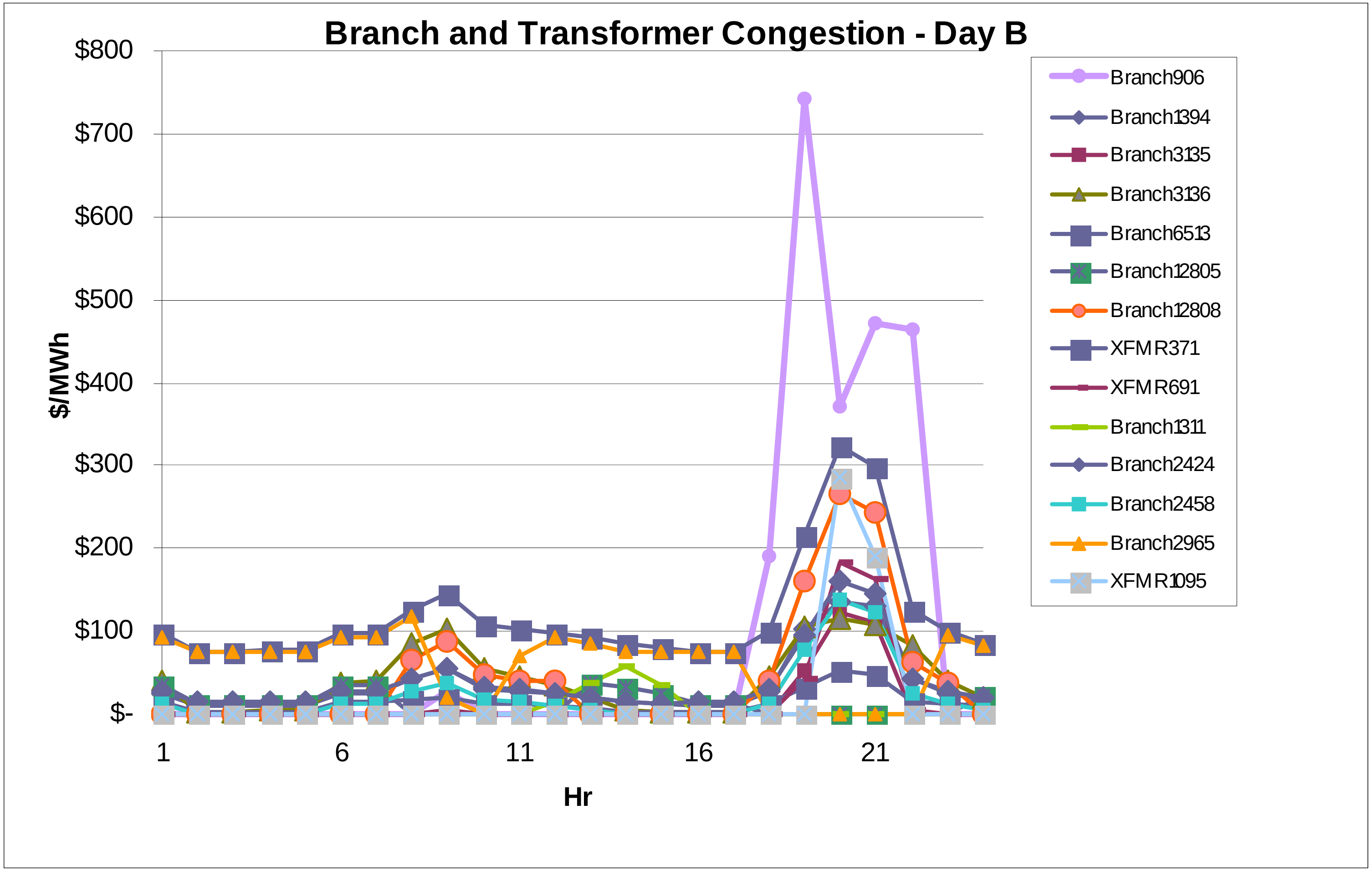


Congestion in the Day Ahead solution

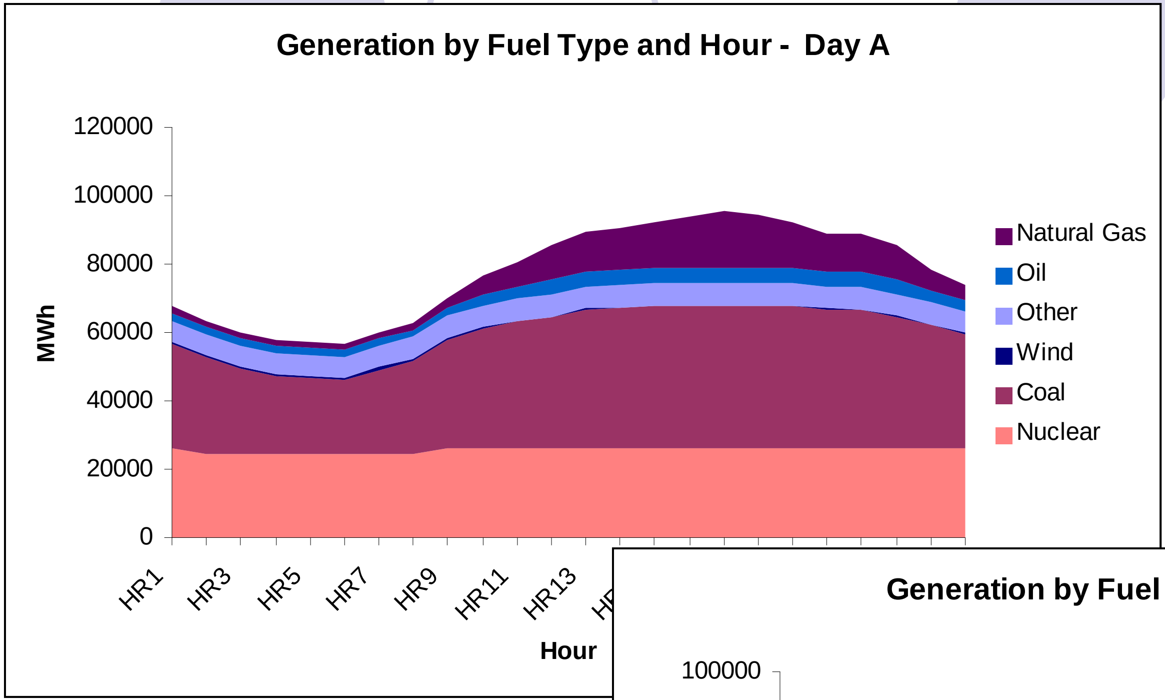
In each scenario, significantly high congestion on multiple transmission elements

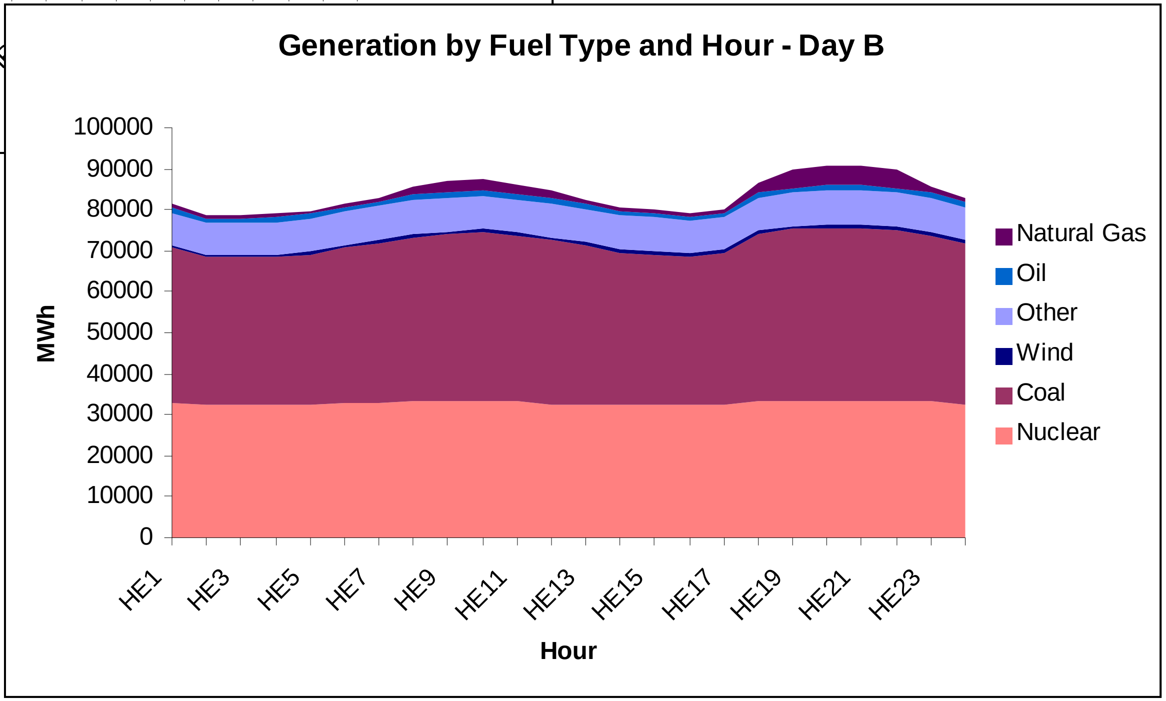


Congestion in the Day Ahead solution



Day Ahead Generation – by Fuel Type





Generation Quantities clearing in the representative day ahead market scenarios

Other formulations of the problem

- "B-Theta" linear approximation of power flow

Whereas the previous formulation in this presentation used shift factors to compute flow on monitored transmission constraints, the B-theta formulation treats voltage angle at each end of the line as decision variables:

$$f_{kt} = -B_k\,(\theta_{nt} - \theta_{mt})$$

Nodal power balance constraints

$$\sum Q_{rt}^{tot} d_r - DEM_{nt}^{fix} + (INJ_{nt}^{loop} + INJ_{nt}^{tie}) - f_{k(n,.)t} + f_{k(.,n)t} = 0$$

With this formulation, the single period (hour) formulation of the model solves in less than two minutes.

Multiple period optimizations with this formulation can grow rapidly in solution time.

Next Steps

- Determine limits on access to the data set
- Evaluating possibility of additional data sets
- Evaluate the need to add additional detail to the data set and model (or a follow on data set)
  - Self Schedules
  - AC parameters
- Acknowledgements
  - Michael Higgins (FERC)
  - Joann Staron (P3 Consulting)
- Questions?