Cascading Failure Curtailment

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Outline

I will argue that....

1. **Preventing cascading failures is uneconomic**
2. **Tight constraints on size are impossible to enforce**
3. **But drastic reductions of size (curtailment) are feasible and economic**

Then I will outline a formulation of the curtailment problem and a solution procedure.

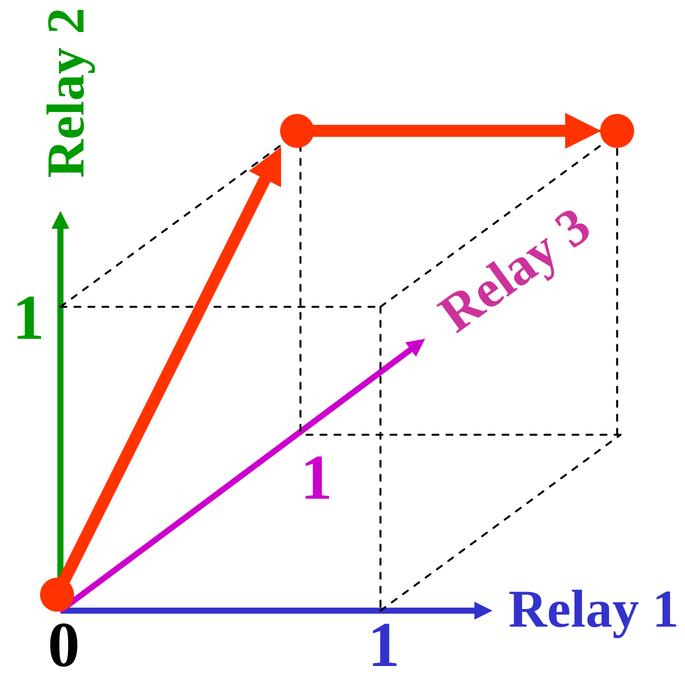
What are cascading failures?

A cascading failure is an automatic sequence of relay operations (a chain reaction) that reduces the network's ability to deliver energy, producing a blackout.

A cascading failure is represented by:

a trajectory through relay space that shows which relays have tripped and in what order.

Each point in relay space is a binary vector. A “1” in the k-th position means that the k-th relay has tripped.



Some properties and propositions...

Prop-1: Cascading failures produce blackouts with large social costs--$ 100 million to 1 billion per year in the USA*

However, these costs are small in comparison to:

- **the costs of all interruptions,**
- **annual electric energy sales,**
- **the costs of major transmission upgrades, and**
- **the annual expenditures on back-up power supplies.**

***Analysis by Paul Hines and Jay Apt**

Prop-2: Emergence rather than instability

- **Cascading failures are emergent behaviors of the relays.**
- **Relays respond to excursions of the state variables.**
- **Only some of these excursions are caused by instabilities**

More specifically.....

1. **The control system of an electric grid is hierarchic.**
2. **The lowest level of this hierarchy contains simple autonomous agents, including thousands of relays.**
3. **The collective behavior of large sets of autonomous agents is emergent.**
4. **Emergent behaviors are often undesirable, can be difficult to predict, and frequently contain jagged features, such as phase transitions and critical points.**

Eg: **percolation net → phase transition**
crowd + fire → panic stricken mob
snow + noise → avalanche
network + multiple contingency → cascading failure

And ....

1. **Relays react to excursions of the continuous variables**
2. **Excursions can be caused by instabilities**
3. **But they are also caused by perfectly stable responses**
4. **The relays (represented by discrete variables) act to limit excursions of the continuous variables, and in doing so, change the configuration of the network**
5. **The question is not whether the continuous variables are stable or unstable; rather, the question is:**
   How much will the configuration change, and will the resulting blackout be large or small?

Prop-3: Stresses—the proximity of state variables to relay thresholds--vary with time and location.

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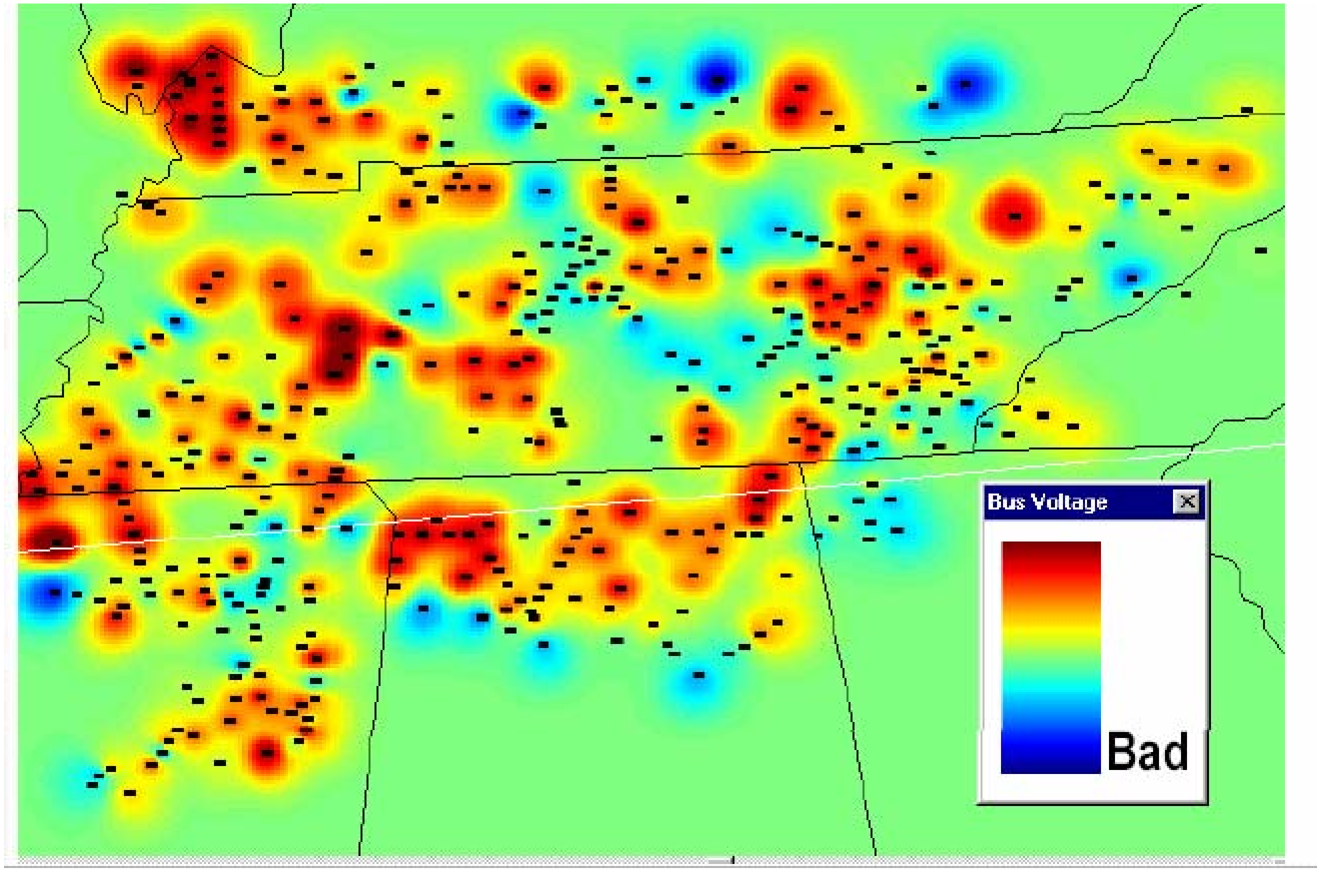
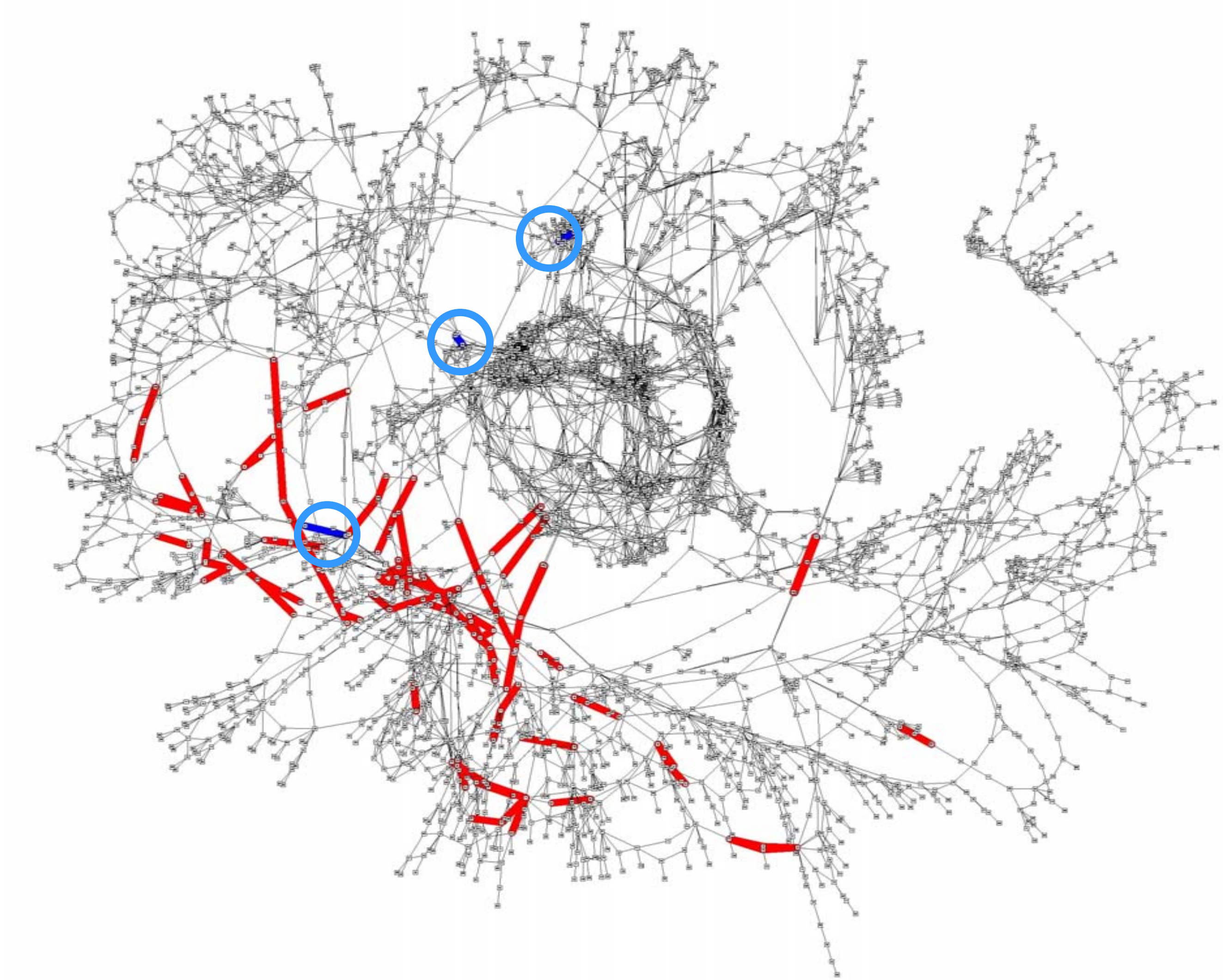


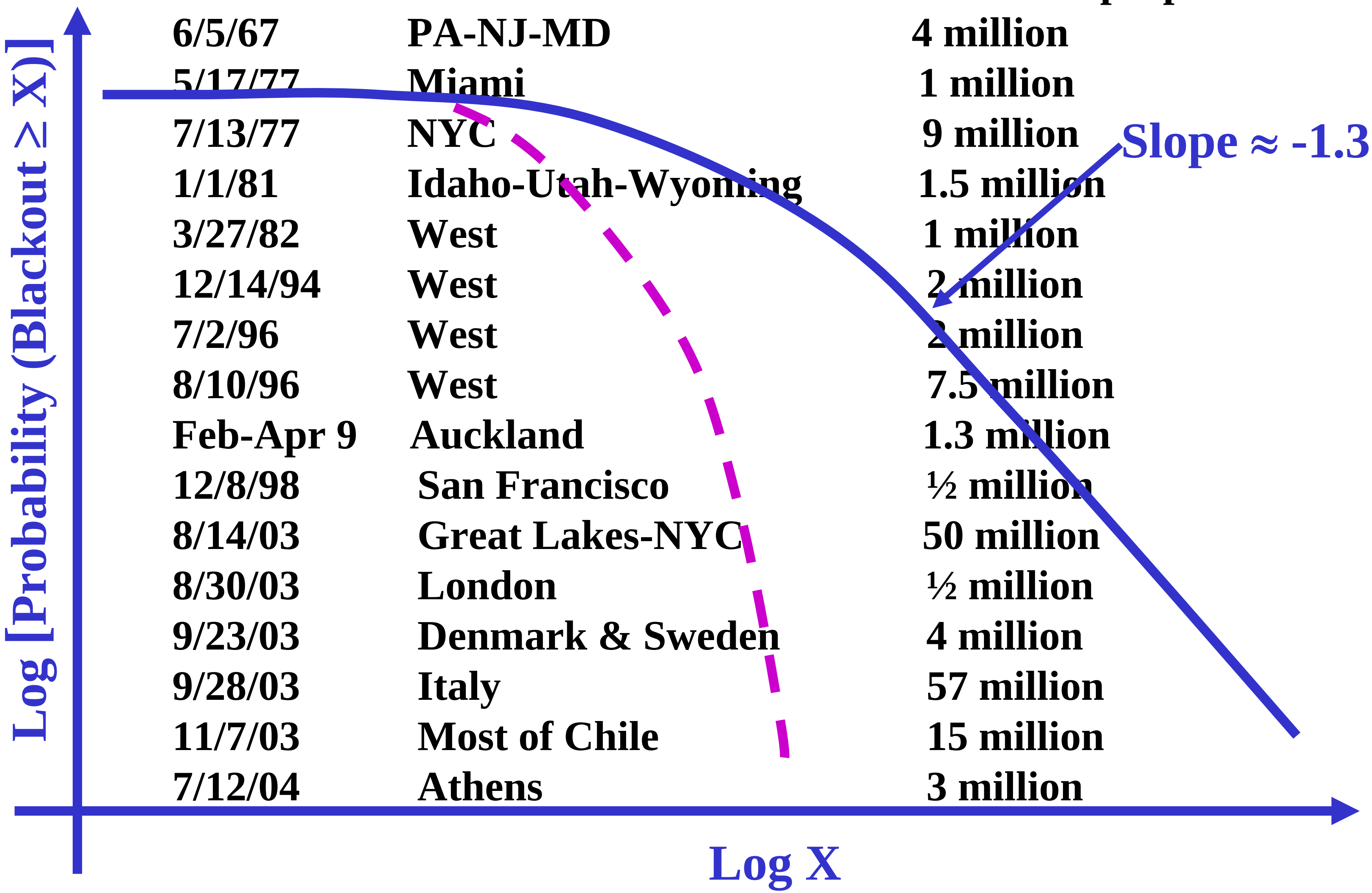
From a talk by Dale Bradshaw

Prop-4: It takes high stresses and a multiple contingency to start a cascade



Prop-5: These conditions happen often enough to give the distribution of blackouts a fat tail

11/9/65	Northeast	30 million people
6/5/67	PA-NJ-MD	4 million
5/17/77	Miami	1 million
7/13/77	NYC	9 million
1/1/81	Idaho-Utah-Wyoming	1.5 million
3/27/82	West	1 million
12/14/94	West	2 million
7/2/96	West	2 million
8/10/96	West	7.5 million
Feb-Apr 9	Auckland	1.3 million
12/8/98	San Francisco	½ million
8/14/03	Great Lakes-NYC	50 million
8/30/03	London	½ million
9/23/03	Denmark & Sweden	4 million
9/28/03	Italy	57 million
11/7/03	Most of Chile	15 million
7/12/04	Athens	3 million



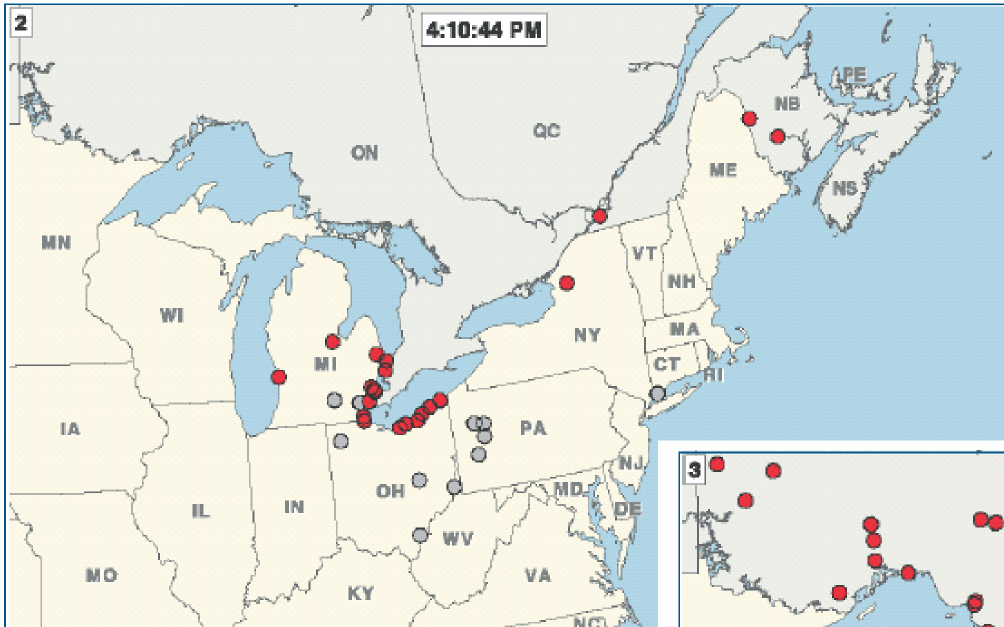
Prop. 6: If the slope of the reverse cumulative distribution's tail is greater than –2,

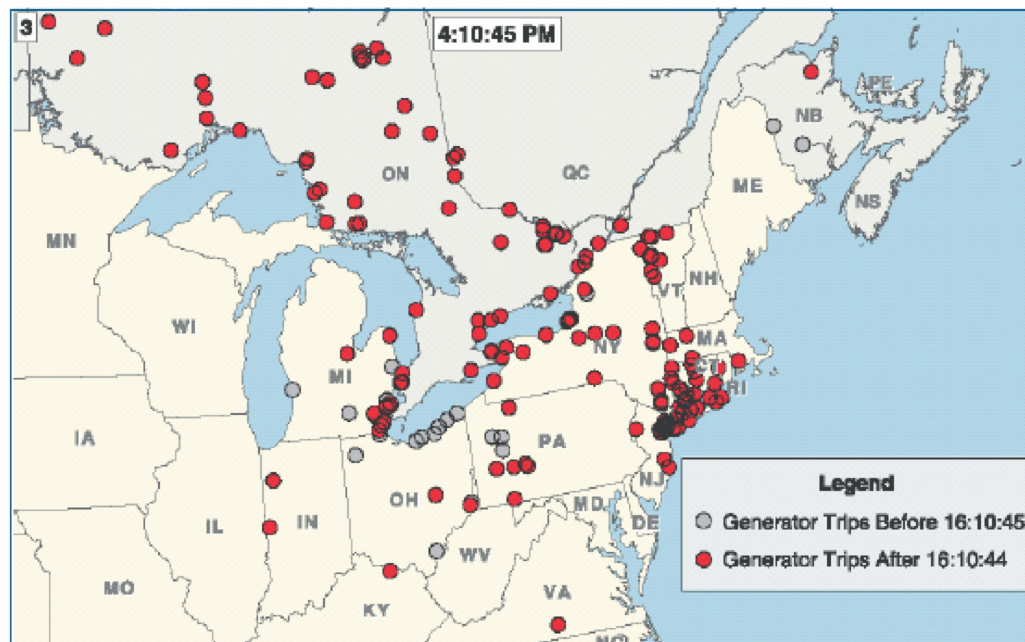
then the product:

[Blackout Probability] [Blackout Size]

increases with Blackout Size, and
the risk is dominated by the larger, less frequent blackouts

Prop 7: The failure front (the next set of devices to be deenergized) can move too fast for human intervention

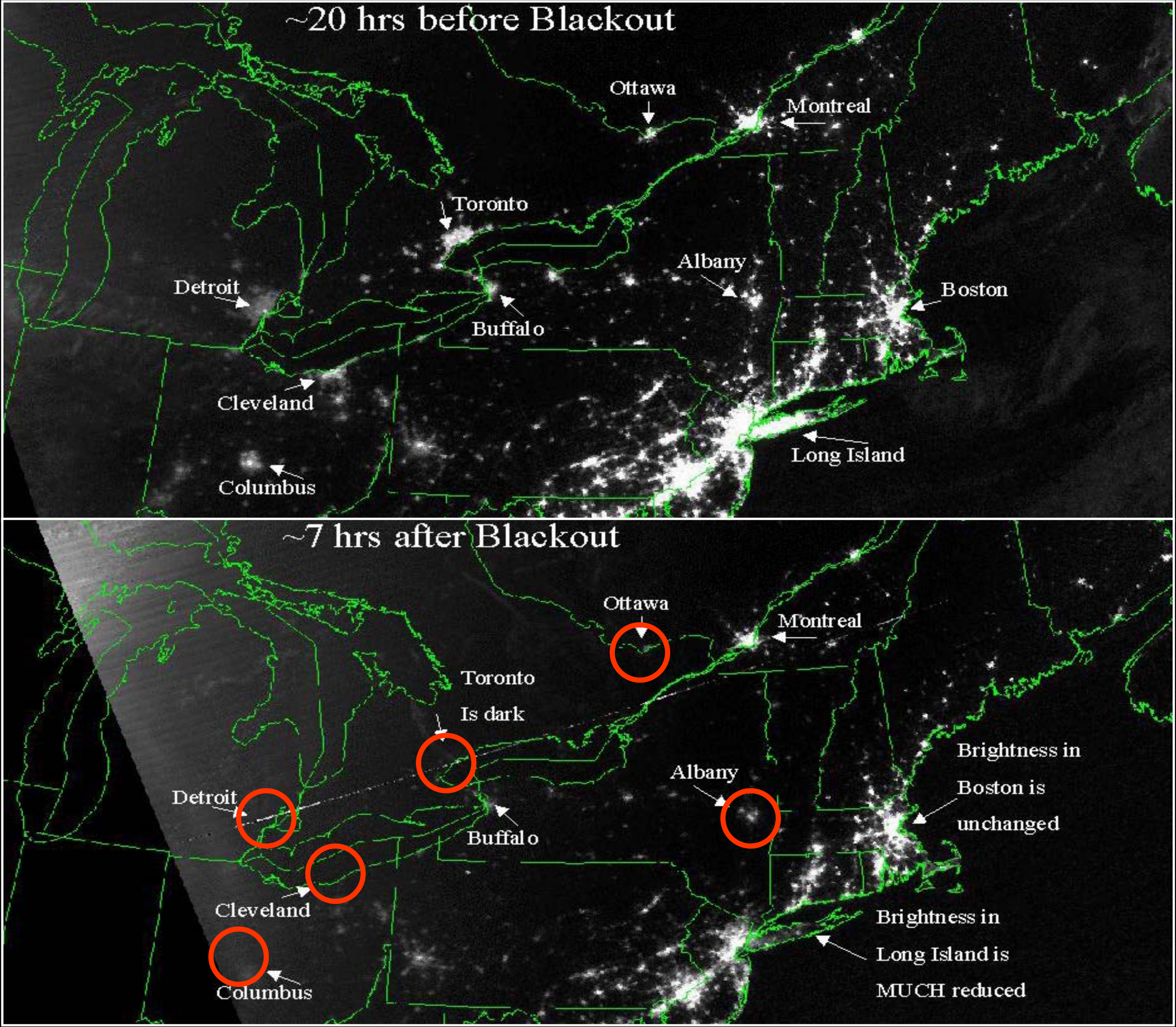




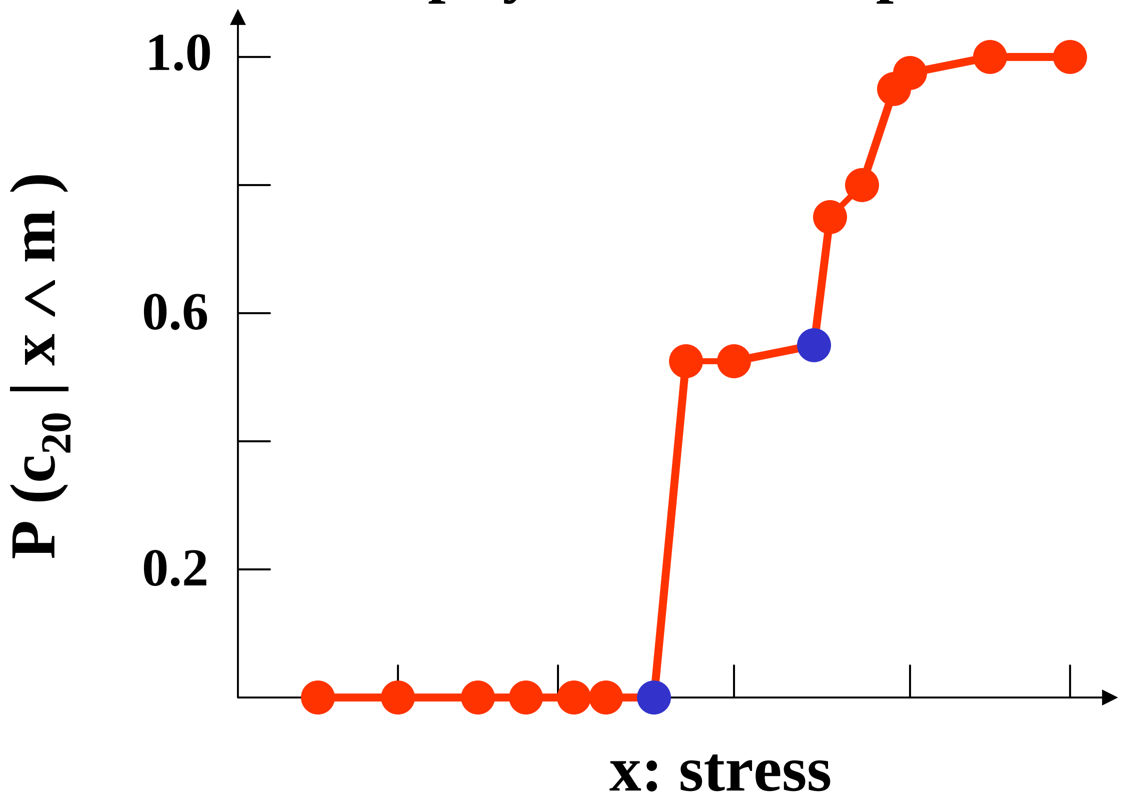
About 100 generator trips in one second

From the Final Report on the Aug. 14 2003 blackout

Prop 8: Cascading failures are self-limiting



Prop 9: There are critical points along many, if not most, of those trajectories through state space along which stress increases monotonically. The probability of cascading failures increases abruptly at a critical point.

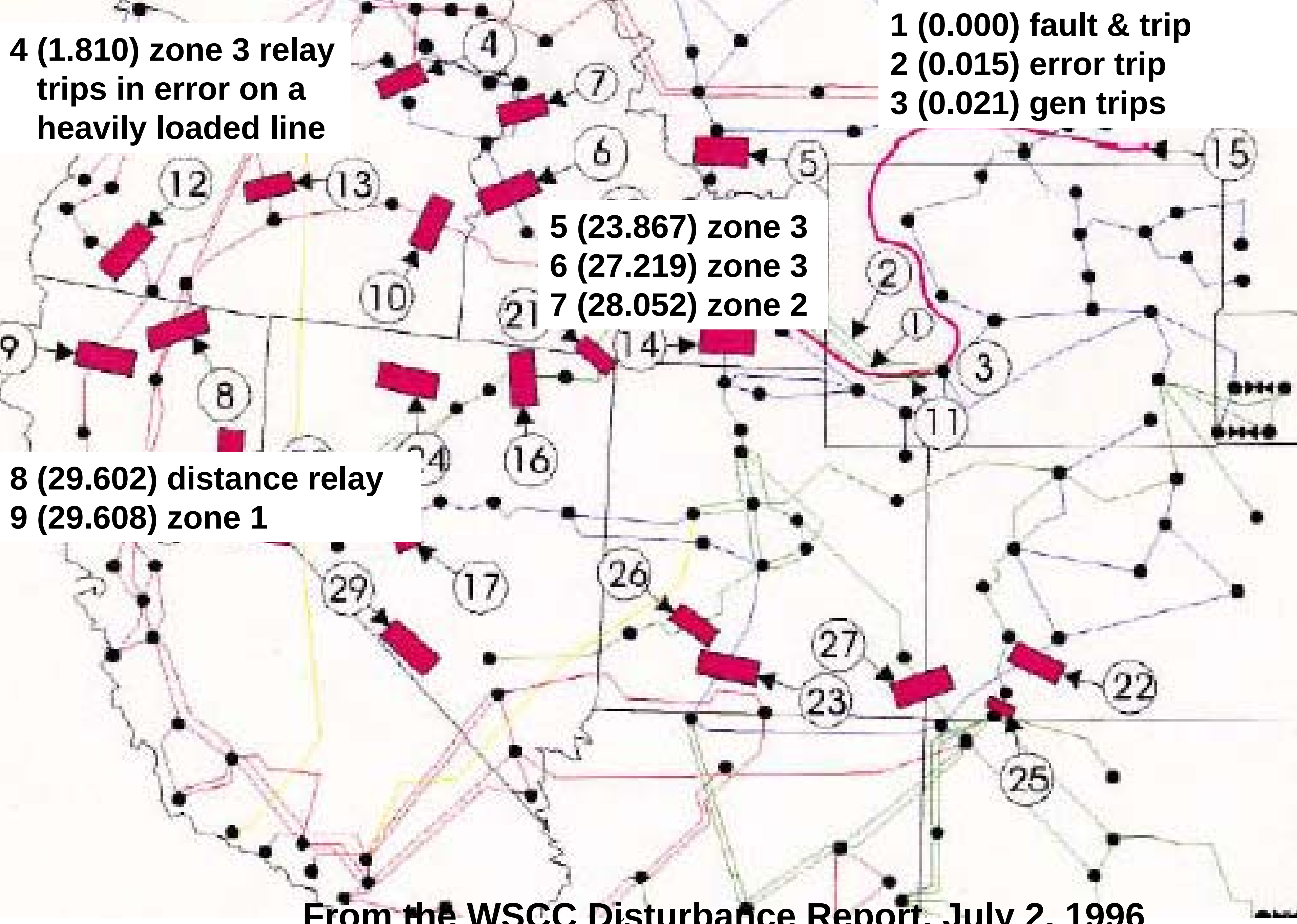


Hence, it would be unwise to use measures of stress as estimates of cascade probability

Prop 10: Both short-and long-range effects are involved in the propagation of the failure front.

Also, relay and other control system malfunctions play an important role in propagating the failure front

More complex protection policies will increase the likelihood of malfunctions, unless the policies are carefully verified.



1 (0.000) fault & trip
2 (0.015) error trip
3 (0.021) gen trips

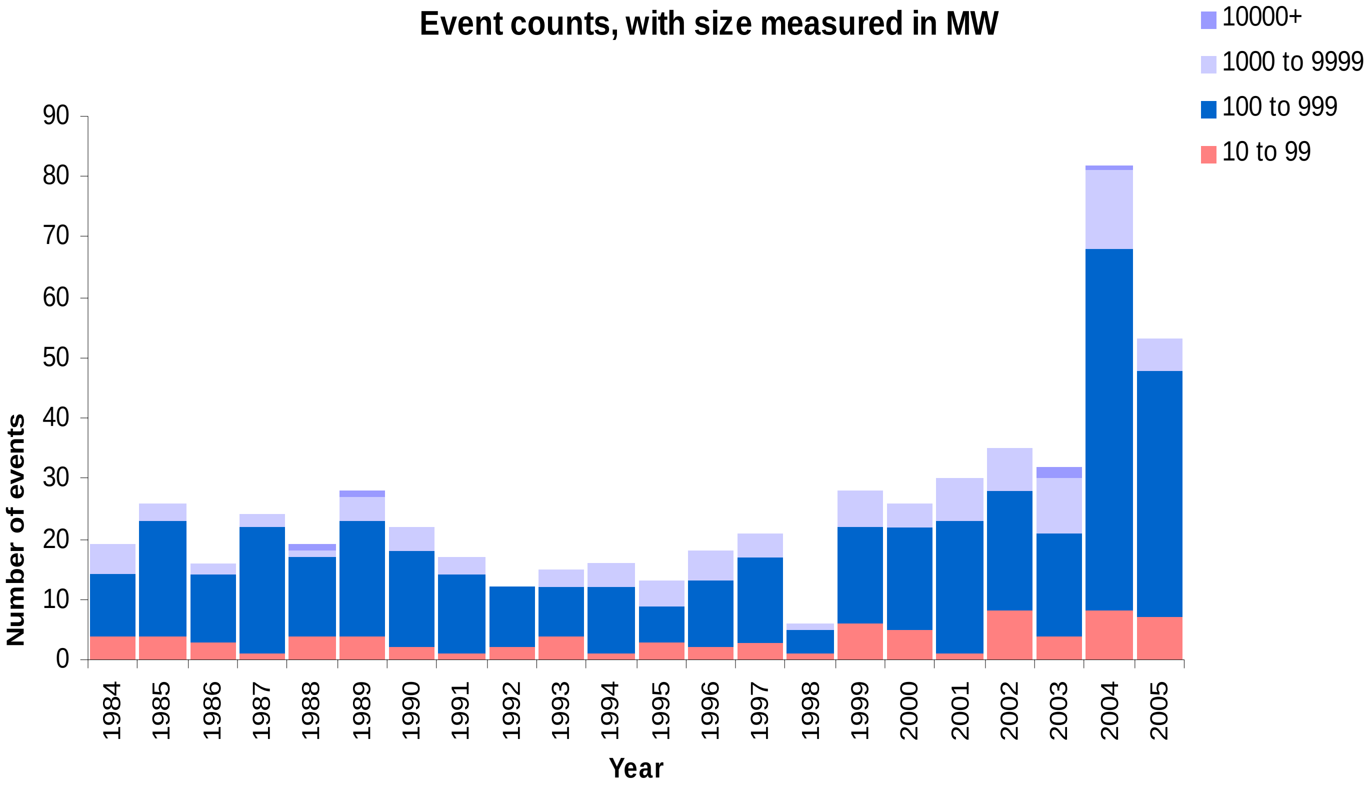
4 (1.810) zone 3 relay trips in error on a heavily loaded line

5 (23.867) zone 3
6 (27.219) zone 3
7 (28.052) zone 2

8 (29.602) distance relay
9 (29.608) zone 1

From the WSCC Disturbance Report, July 2, 1996

Prop 11: Investments in equipment and new technologies have not reduced the frequency or impact of cascading failures



Prop 12: Contingency-Constrained-Optimal-Power-Flows cannot be used to eliminate cascading failures

The feasible region for:

a) economically viable solutions, and

b) any reasonable set of (N-k) contingencies

is empty.

Prop 13: But there are ways to curtail cascades and drastically reduce their social costs. (Existing control policies are sub-optimal w.r.t. social cost.)

Post-cascade analysis invariably reveals several different and relatively inexpensive actions, any of which would have shortened the cascade, had the actions been taken soon after the cascade began.

These actions are cascade-specific.

I believe that optimal, or near-optimal actions can be calculated in real-time, quickly enough to be useful.

Prop 14: Electric power networks are stochastic hybrid systems. Their operation involves:

- **Contingencies and other uncertainties**
- **Continuous variables**
- **Discrete variables**

If optimal-cascade-stopping actions are to be calculated in real-time, then:

- **the network's hybrid characteristics must be taken into account**
- **the problem formulation must be correct and precise**

(The best possible solution to the wrong problem is still the wrong solution.)

Past attempts at cascade control have addressed only small parts of the full problem

Summary of Properties and Conjectures

1. **The risk of cascading failures is dominated by the largest possible failures.**
2. **Proactive measures are economically unjustifiable. Neither the addition of transmission capacity nor the adjustment of pre-cascade operating points is an economic means for preventing large cascading failures.**
3. **But it is possible to reduce the social costs of both large and small cascades by reactive controls, including: a) a system to curtail (shorten) cascades, and b) a system of back-ups to reduce the ill effects of blackouts**
4. **Optimal curtailment requires the problem to be formulated fully and correctly**

Curtailment

The Curtailment Problem

Once a cascade has begun, calculate continuous and discrete controls so as to

Minimize: **The social cost of the cascade (and controls)**

Subject to: **No damage to equipment**

Leave protection thresholds unchanged

An MPC (Model Predictive Control) formulation for the time horizon: $\{t_0, t_1, ..., t_N\}$

Control variables for period-1

Social cost

All variables for period-1

Minimize $\quad f(Z_0, Z_1, ..., Z_N)$

$U_1, ..., U_N$

Subject to: $\quad M(Z_n, X_{n+1}) = 0, \qquad n = 0, 1, ..., N-1$

A hybrid model that includes continuous dynamics and relay models

Solving the Problem

There are no rigorous algorithms

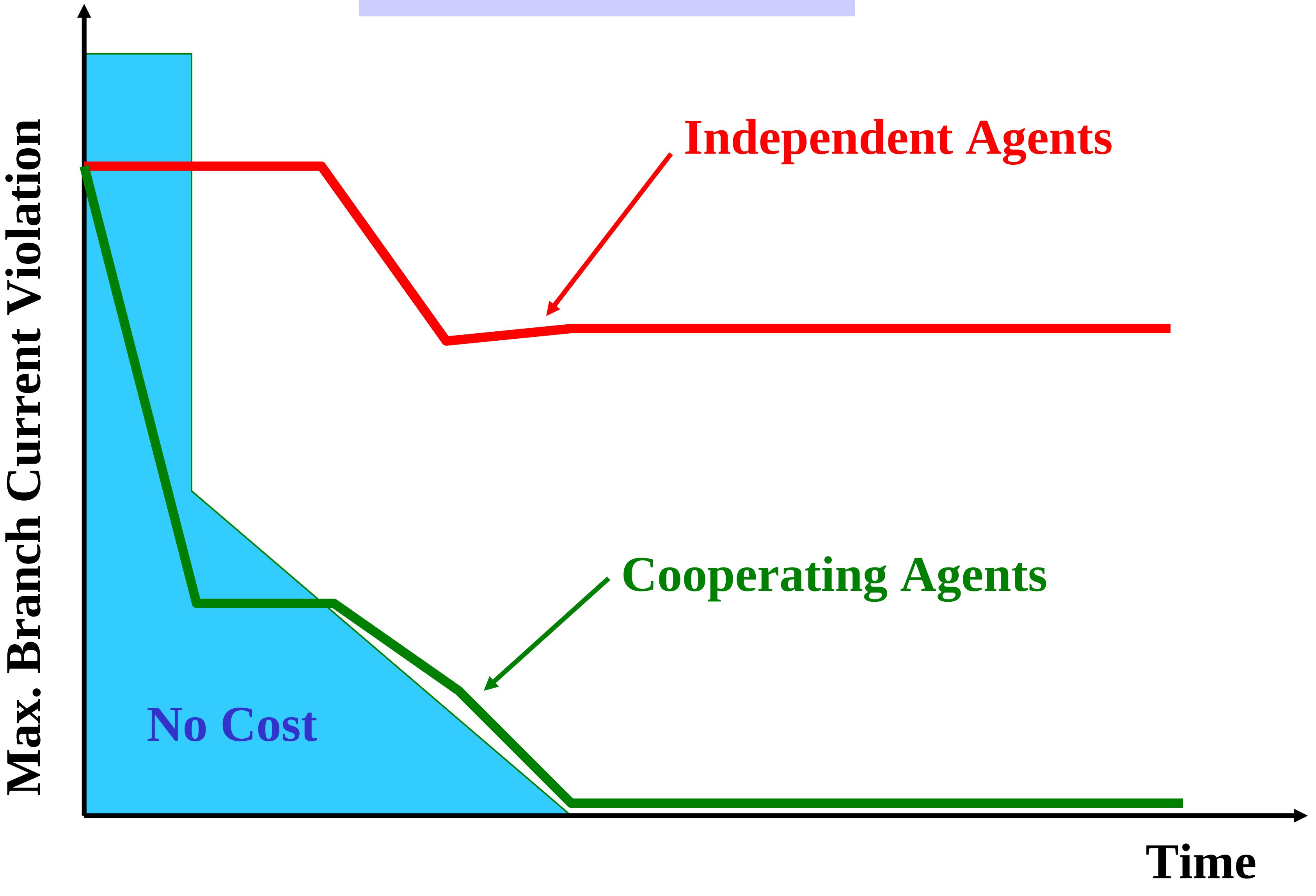
Centralized algorithms would seem to be inadequate

Instead, we use a system of distributed autonomous agents.

Key issues:

- **the division of labor**
- **the coordination of labor**

TYPICAL RESULTS



CONCLUSIONS

Can cascading failures be eliminated?

No! Not unless networks are operated at uneconomically low stresses.

Any heuristic policy to prevent or control cascading failures is only as good as the contingencies over which it is tested. We can only test a small fraction of the contingencies that are possible. At high stresses, the system will be vulnerable to some, if not many, of the untested contingencies. Invariably, some of these untested contingencies will occur.

But through autonomous agents and optimal curtailment, the network's reactions can be dramatically improved.