PEER 2003 ANNUAL MEETING

Session 7: Distributed Network Systems

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Costs and Benefits in Seismic Risk Analysis

Seismic Hazard Simulation of Bay Area Highway Network, CA
Transportationportation Analysis

Saturday, March 8, 2003

Palm Springs, California

Charge

5) Assuming SRA can become reliable, how would users establish acceptability criteria for seismic losses from a (Seismic Risk) analysis? What costs and benefits need to be considered?

JIM: Please focus on question #5. Personally, I would like to see a clear and simple overview of basic types of costs that SHOULD be considered (if we could), and those that ARE considered using current models. It would be very helpful to illustrate this with results from your NSF Elysian Scenario study as well as to illustrate key sensitivities in the analysis (say change in costs associated with alternate closure criteria). Lastly, I think a clear discussion of how to establish acceptability criteria for seismic losses is needed.

Time Limit: 20 Minutes.

Summary

- Benefits are costs avoided. An optimal plan requires benefit estimates that are full, comprehensive, and system-wide. This is a difficult problem at the level of large metropolitan areas.

- Pre- and post-event earthquake decisions (mitigation and response decisions) are intended to reduce:
    - replacement and repair costs associated with structures and building contents (what regional scientists and economists call "replacement and repair costs" and what earthquake engineers call "direct costs");
    - the opportunity costs associated with losing productive access to the capital plant when facilities are damaged (what regional scientists and economists call "direct costs" and what earthquake engineers call "indirect costs");
    - the secondary costs associated with losses to suppliers when producers stop bidding on production inputs because of damage to capital facilities (what regional scientists and economists call "indirect costs," and what earthquake engineers call "huh?"--to be fair, show a regional scientist a hysteresis curve, and s/he will respond with a heartfelt "huh?");

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- the secondary costs associated with losses to suppliers of labor (households) when producers and their other suppliers stop bidding on labor because of damage to capital facilities (what regional scientists and economists call "induced costs");
- the costs associated with interruptions in services provided by public infrastructure systems (lifelines);
- the costs associated with injury and loss of life, which range from a lower bound defined by the net present value of lost wages (the value of time exchange on the market for labor) to an upper bound of infinity (the value of time in use when you are trying hard to stay alive);
- the direct costs of productivity losses (administrative costs) associated with financing pre- and post-event decisions.
- the indirect and induced costs of productivity losses (the full economic burden of taxation and code enforcement) associated with financing pre- and post-event decisions.

- From a policy-making and political perspective, we would like to know what income groups, economic sectors, and communities benefit from pre- and post-event decisions, and who pays (incidence).

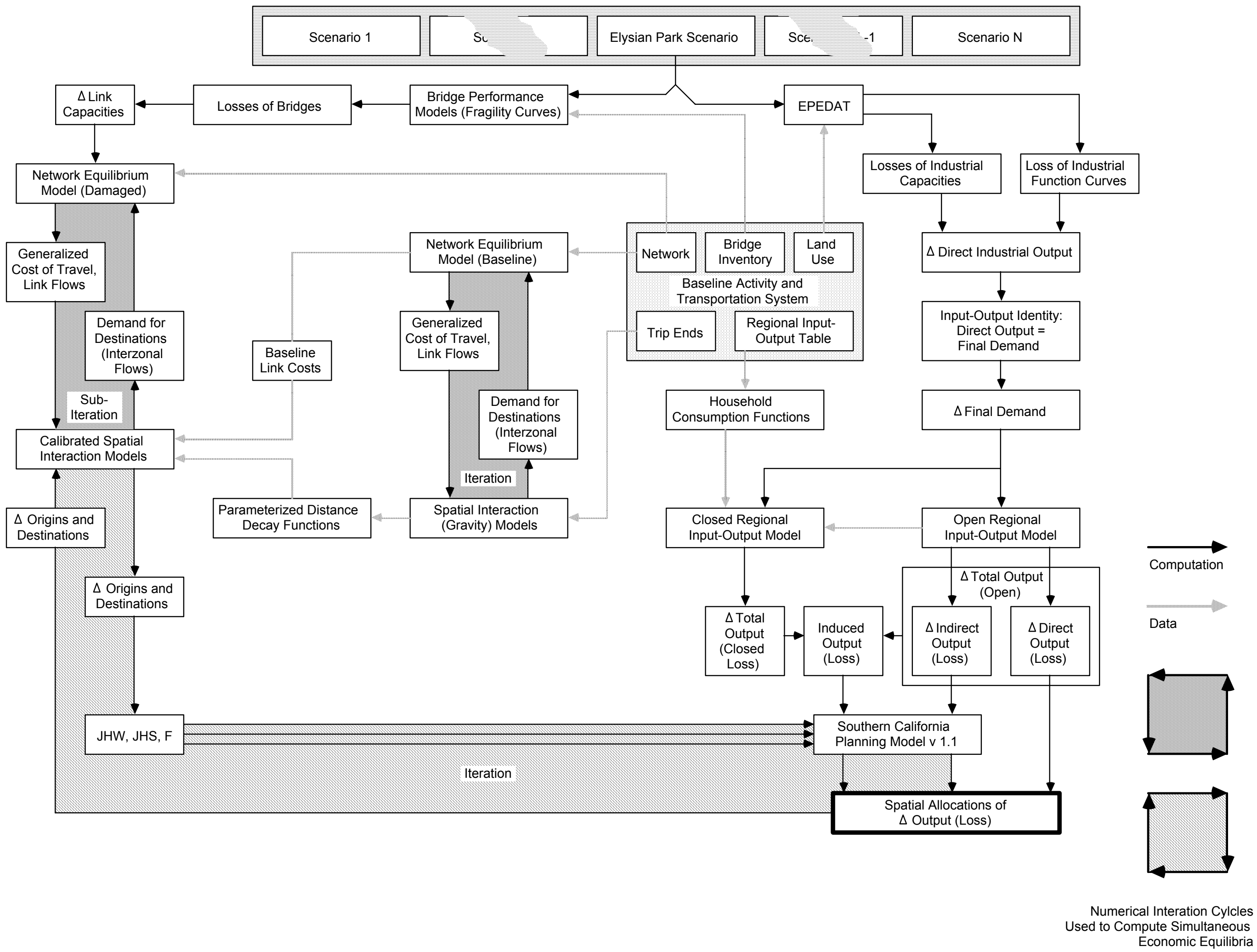
- In previous research funded by NSF and PEER, we have specified a computable model that shows the effects of earthquakes on transportation networks, building stocks, and regional economic activities. This model accounts for interactions between the urban economy and the transportation network.

- Previous research done with MCEER and FHWA has focused more on a probabilistic treatment of hazards and has suppressed representation of the urban economic activity system.

- Research done at PEER and MCEER has been metropolitan and intra-urban. Work done at MAE has been regional and interurban.

- Given access to data, computing resources, and efficient algorithms, we can and have estimated:
  - direct costs (we have paid little attention to replacement costs);
  - indirect costs;
  - induced costs;
  - costs associated with damage to transportation infrastructure (congestion); and
  - the distribution of costs by sector, income group and location.

- We have paid little attention to:
  - costs associated with damage to other types of infrastructure (water distribution, gas distribution, electric power distribution) or interactions between infrastructure failures;
  - injuries and loss of life;
  - the probability distribution of costs, except in the case of damage to transportation networks;
  - the administrative costs of new public policy.



SCPM2

Source: Cho, Gordon, Moore II, Richardson, Shinozuka, and Chang (2001) "Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Urban Earthquake," Journal of Regional Science, **41**: 39-65.

Table 1: Direct Losses Resulting From Structure Damage ($Billions): Elysian Park Magnitude 7.1 Earthquake

Structure Type	Lower Bound	Upper Bound
Residential	$ 14.5 billion	$ 24.2 billion
Nonresidential		
Commercial	4.1	6.9
Industrial	2.7	4.5
Other	0.4	0.6
Nonresidential Subtotal	7.2	12.0
Structure Subtotal	$ 21.7 billion	$ 36.2 billion
Content Losses	12.2	20.4
Total	$ 33.9 billion	$ 56.6 billion

Source: Cho, et al (1999) Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Earthquake, Volume II of a Final Technical Report to the National Science Foundation for Award CME 9633386 (EHM), available at http://www.usc.edu/schools/sppd/eqloss/index.html

Table 2: Summarizing Damage States for 200 Monte Carlo Simulations of the Elysian Park Scenario

Bridge Damage Index (BDI) Threshold Value for Bridge Closure	Number of Damaged Directional Links	Number of Damaged Directional Lane Miles	Baseline Passenger Car Unit (PCU) Miles Associated w/Damaged Links	Qualitative Description
BDI Threshold = .30[a] Maximum[b] of 200 Cases	326	1,305.7	10,653,932	Very disruptive bridge impacts, conservation bridge closure criteria
BDI Threshold = .30 Median of 200 Cases	277	1,020.2	7,733,999	Representative bridge impacts, conservation bridge closure criteria
BDI Threshold = .75[c] Maximum of 200 Cases	122	479.6	3,877,952	Very disruptive bridge impacts, risky bridge closure criteria
BDI Threshold = .75 Median of 200 Cases	84	309.0	2,257,160	Representative bridge impacts, risky bridge closure criteria

Notes:
- a Bridges achieving a Bridge Damage Index of 0.30 (moderate damage) or greater are closed to traffic. This is a risk averse criterion that emphasizes post-event public safety, but greatly diminishes the capacity of the transportation system.
- b Each of the Monte Carlo simulations for the Elysian Park scenario is ranked according to the baseline Passenger Car Unit (PCU) Hours associated with damaged links. The scenario with the maximum score corresponds to the maximum displacement in terms of baseline vehicle miles traveled. The simulation with the median score is more representative of the stochastic process parameterized by the bridge fragility curves.
- c Bridges achieving a Bridge Damage Index of 0.75 (major damage) or greater are closed to traffic. This is a risk tolerant criterion that emphasizes post-event transportation supply, but increases risks to the public.

Source: Cho, et al (1999) Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Earthquake, http://www.usc.edu/schools/sppd/eqloss/index.html

Table 3: Total Loss ($Billions): Elysian Park Magnitude 7.1 Earthquake, Median Simulated Disruption to Baseline Transportation (Closure at BDI $\geq$ 0.30)

Loss Type	**Baseline**		**Elysian Park Scenario: Conservative Bridge Closure Criterion**	
A Structure Loss[a]			$ 45.250 billion (44.2% of total)	
Business Loss				
Direct Loss[b]			28.155	
Indirect Loss[c]			9.627	
Induced Loss[d]			8.955	
B Business Loss Subtotal			46.737 billion (45.7% of total)	
Network Costs[e]	PCU Minutes	$ Billions	PCU Minutes	$ Billions
Personal Travel Cost	85,396,813.	21.290	117,493,842.	29.291
Freight Cost	10,298,781.	4.550	15,602,872.	6.893
Total Travel Cost	95,695,594.	25.839	133,096,713.	36.184
Network Loss = Δ Network Costs			PCU Minutes	$ Billions
Δ Personal Travel Cost			32,097,029.	8.002
Δ Freight Cost			5,304,091	2.343
C Δ Total Travel Cost			37,401,119.	10.345 (10.1% of total)
Loss Total = A + B + C			$ 102.332 billion	

Notes: a. Midpoint of interval in Table 1. b. EPEDAT, EQE International. c. RSRI Model.
d. Difference between the RSRI solution with the processing sector closed with respect to labor and the RSRI solution with the processing sector open with respect to labor.
e. Network cost is the generalized total transportation cost associated with a simultaneous equilibrium across choice of destinations and routes. These estimates reflect 365 travel days per year, an average vehicle occupancy of 1.42 for passenger cars, 2.14 passenger car units per truck, a value of time for individuals of $6.5/hour, and $35/hr for freight.

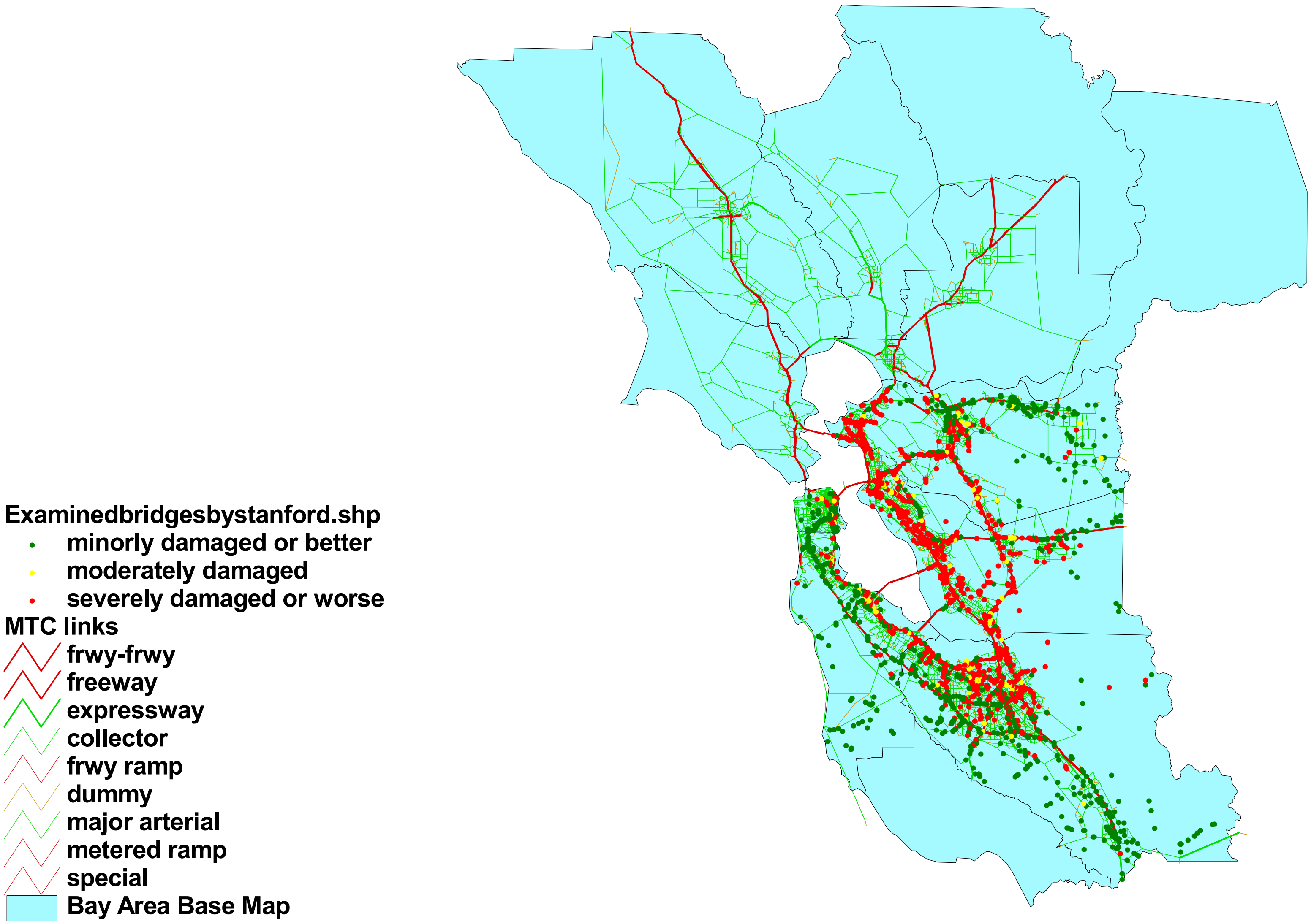
Source: Cho, et al (1999) Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Earthquake, http://www.usc.edu/schools/sppd/eqloss/index.html

Table 4: Total Loss ($Billions): Elysian Park Magnitude 7.1 Earthquake, Median Simulated Disruption to Baseline Transportation (Closure at BDI $\geq$ 0.75)

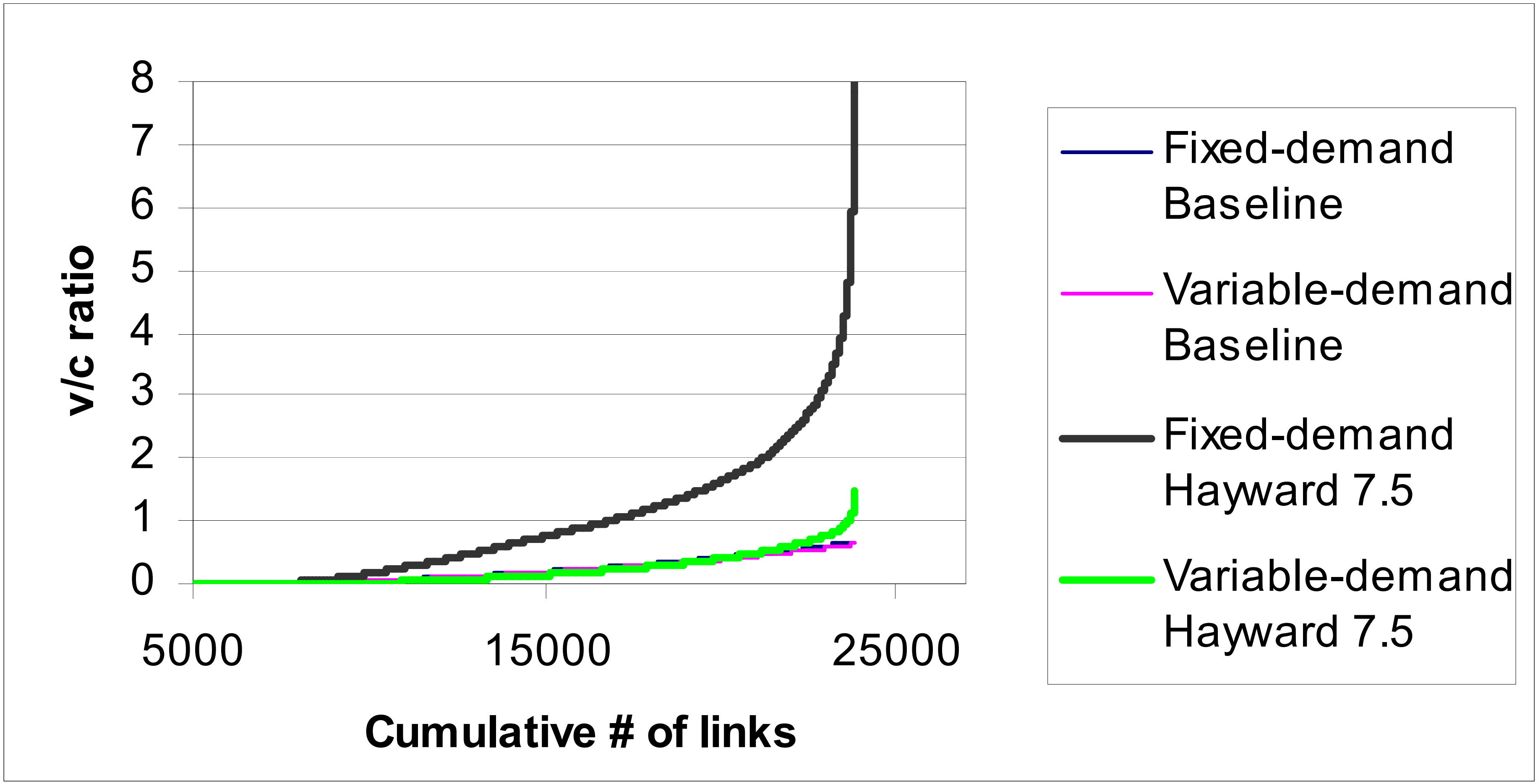
Loss Type	**Baseline**		**Elysian Park Scenario: Risky Bridge Closure Criterion**	
A Structure Loss[a]			$ 45.250 billion (48.4% of total)	
Business Loss				
Direct Loss[b]			28.155	
Indirect Loss[c]			9.627	
Induced Loss[d]			8.955	
B Business Loss Subtotal			46.737 billion (50.1% of total)	
Network Costs[e]	PCU Minutes	$ Billions	PCU Minutes	$ Billions
Personal Travel Cost	85,396,813.	21.290	89,945,131.	22.424
Freight Cost	10,298,781.	4.550	10,966,123.	4.844
Total Travel Cost	95,695,594.	25.839	100,911,255.	27.268
Network Loss = Δ Network Costs			PCU Minutes	$ Billions
Δ Personal Travel Cost			4,548,318.	1.134
Δ Freight Cost			667,343	0.295
C Δ Total Travel Cost			5,215,661.	1.429 (1.5% of total)
Loss Total = A + B + C			$ 93.416 billion	

Notes: Suppressed, same as Table 3.
Source: Cho, et al (1999) Integrating Transportation Network and Regional Economic Models to Estimate the Costs of a Large Earthquake, http://www.usc.edu/schools/sppd/eqloss/index.html

Bay Area Street Network and Bridges



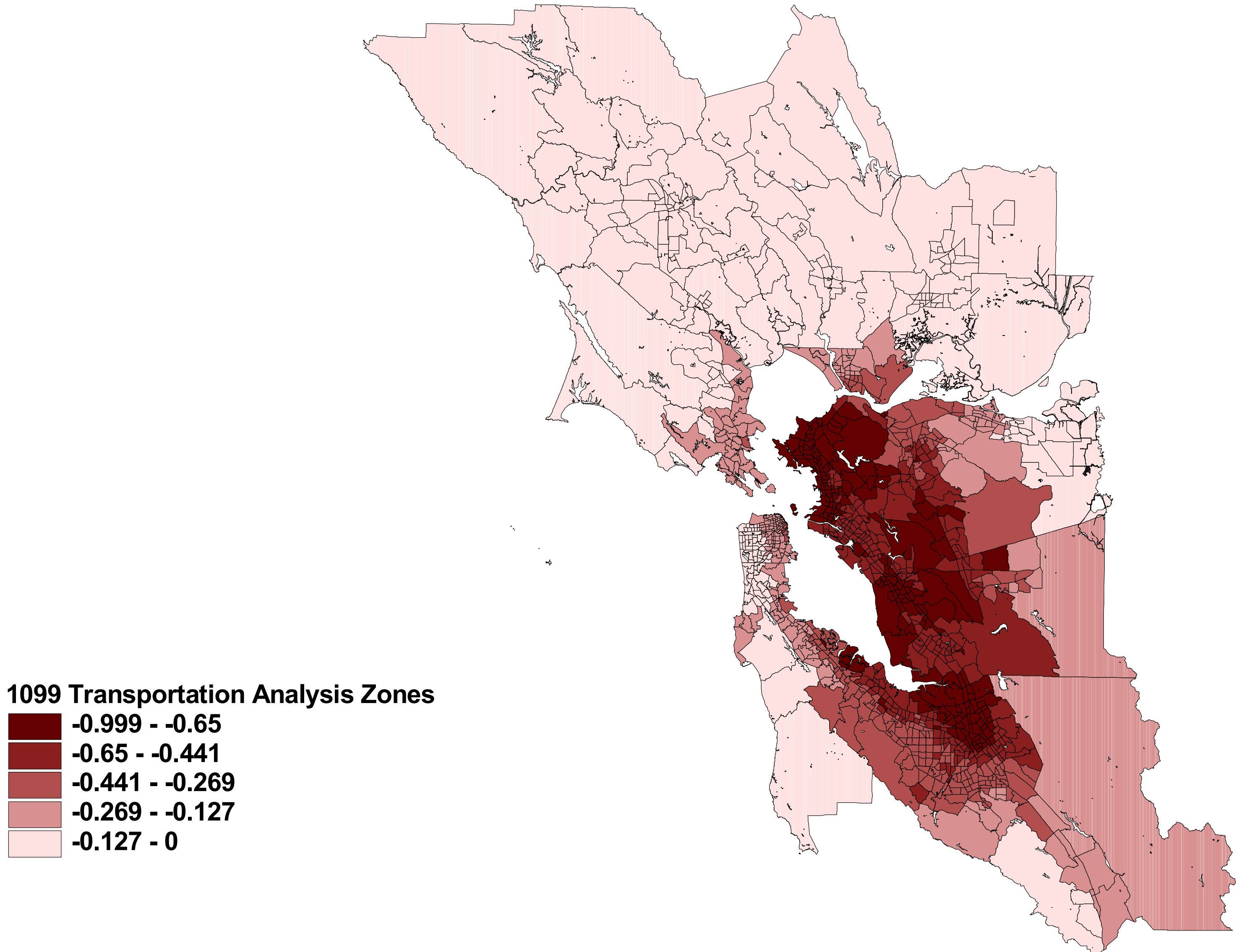
Comparison of v/c Ratios between the Fixed-demand and the Variable-demand Models



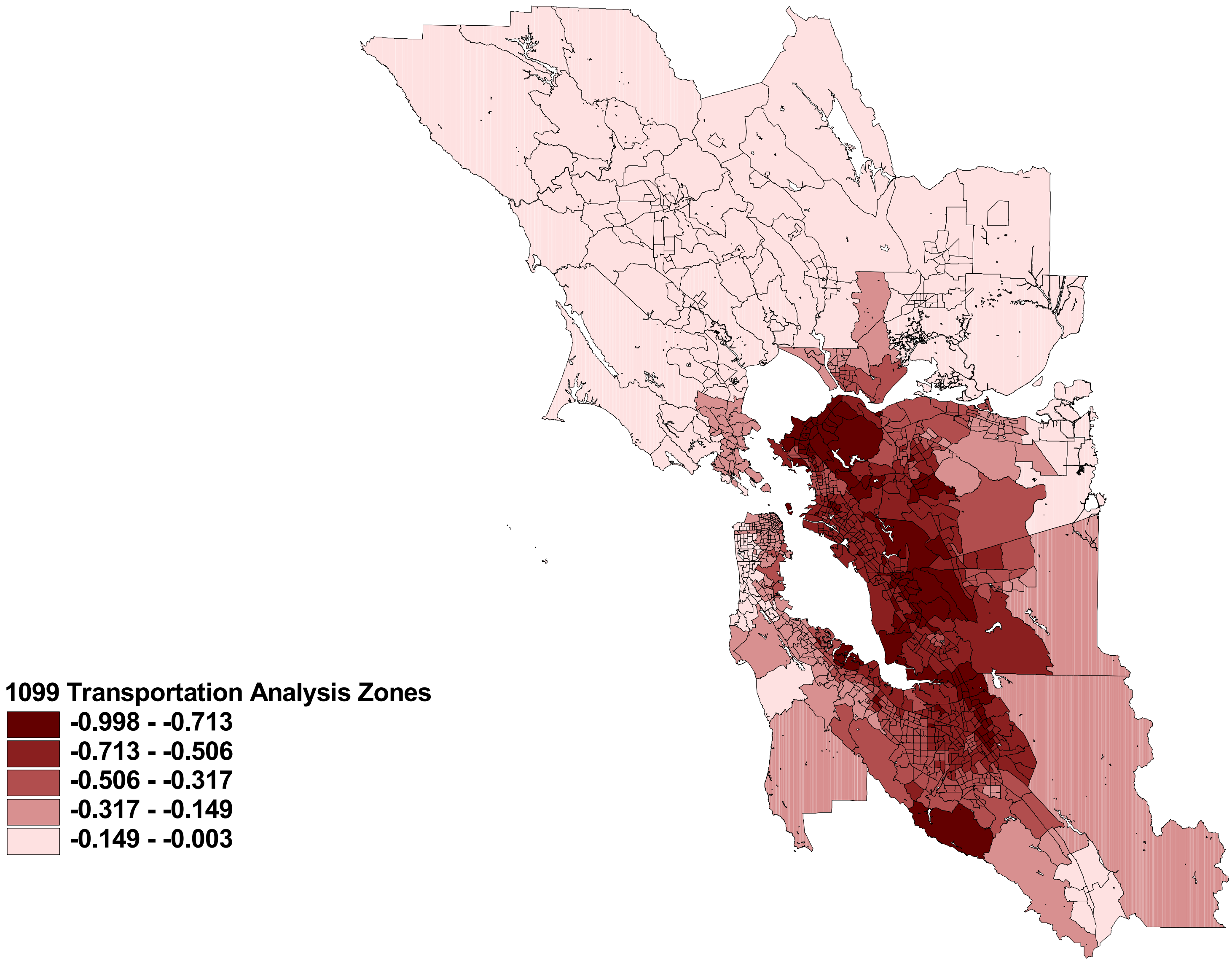
v/c Ratio Comparison (Fixed-Demand vs. Variable-Demand Models)

LINK TYPE	Data	fixed-demand	variable-demand
frwy-frwy connection	Average of V/C	0.52	0.18
	Max of V/C2	4.81	1.28
freeway	Average of V/C	0.71	0.22
	Max of V/C2	4.94	1.28
expressway	Average of V/C	1.07	0.26
	Max of V/C2	9.29	1.45
collector	Average of V/C	0.99	0.16
	Max of V/C2	11.81	1.28
freeway ramp	Average of V/C	0.81	0.20
	Max of V/C2	11.21	1.44
dummy link	Average of V/C	0.01	0.00
	Max of V/C2	0.32	0.06
major arterial	Average of V/C	1.04	0.25
	Max of V/C2	8.64	1.46
metered ramp	Average of V/C	1.58	0.36
	Max of V/C2	7.47	1.39
special	Average of V/C	3.85	0.58
	Max of V/C2	4.59	0.60
Total Average of V/C		0.77	0.17
Total Max of V/C2		11.81	1.46

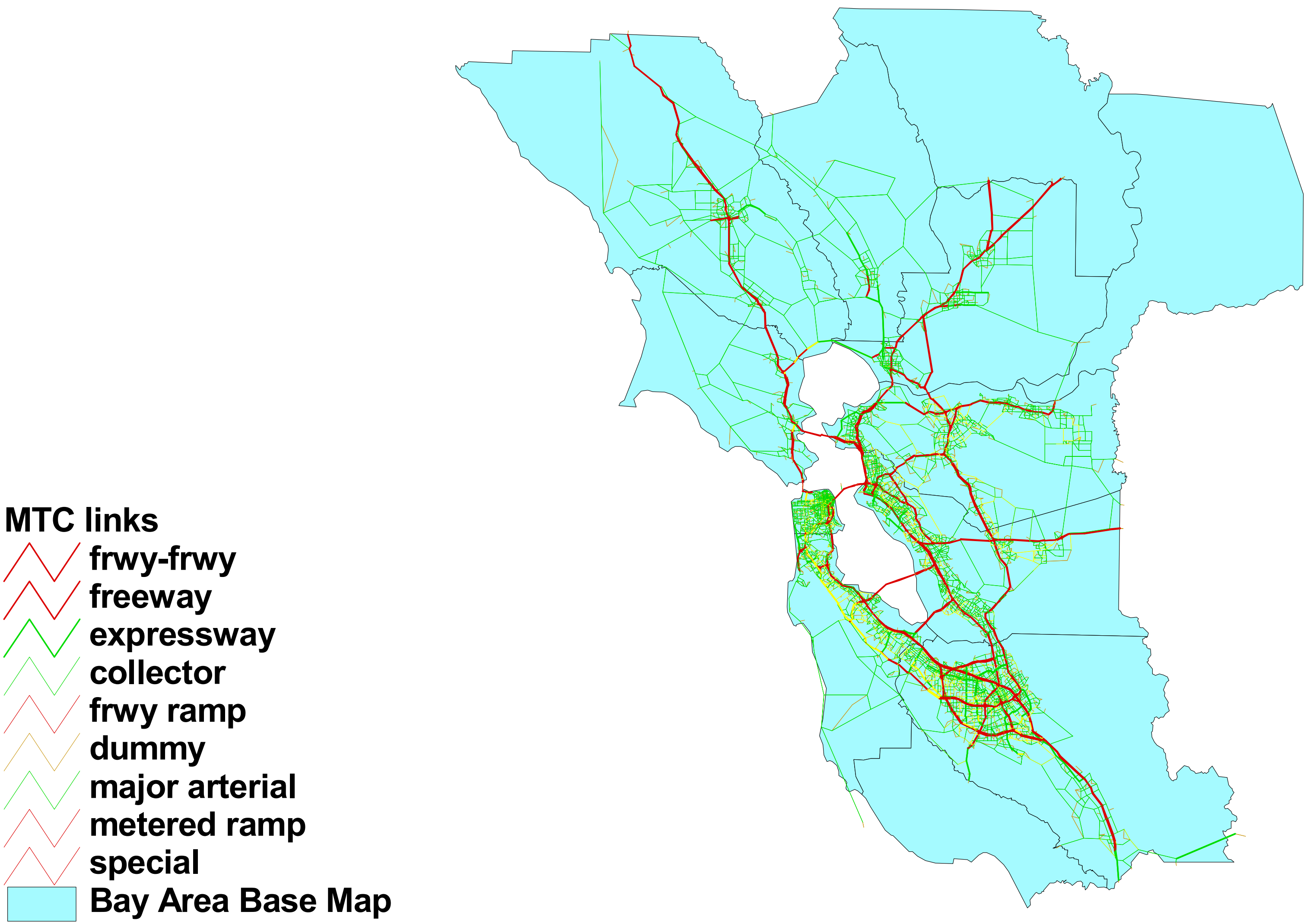
Proportionate Difference in Trip Attraction, Variable vs. Fixed Demand



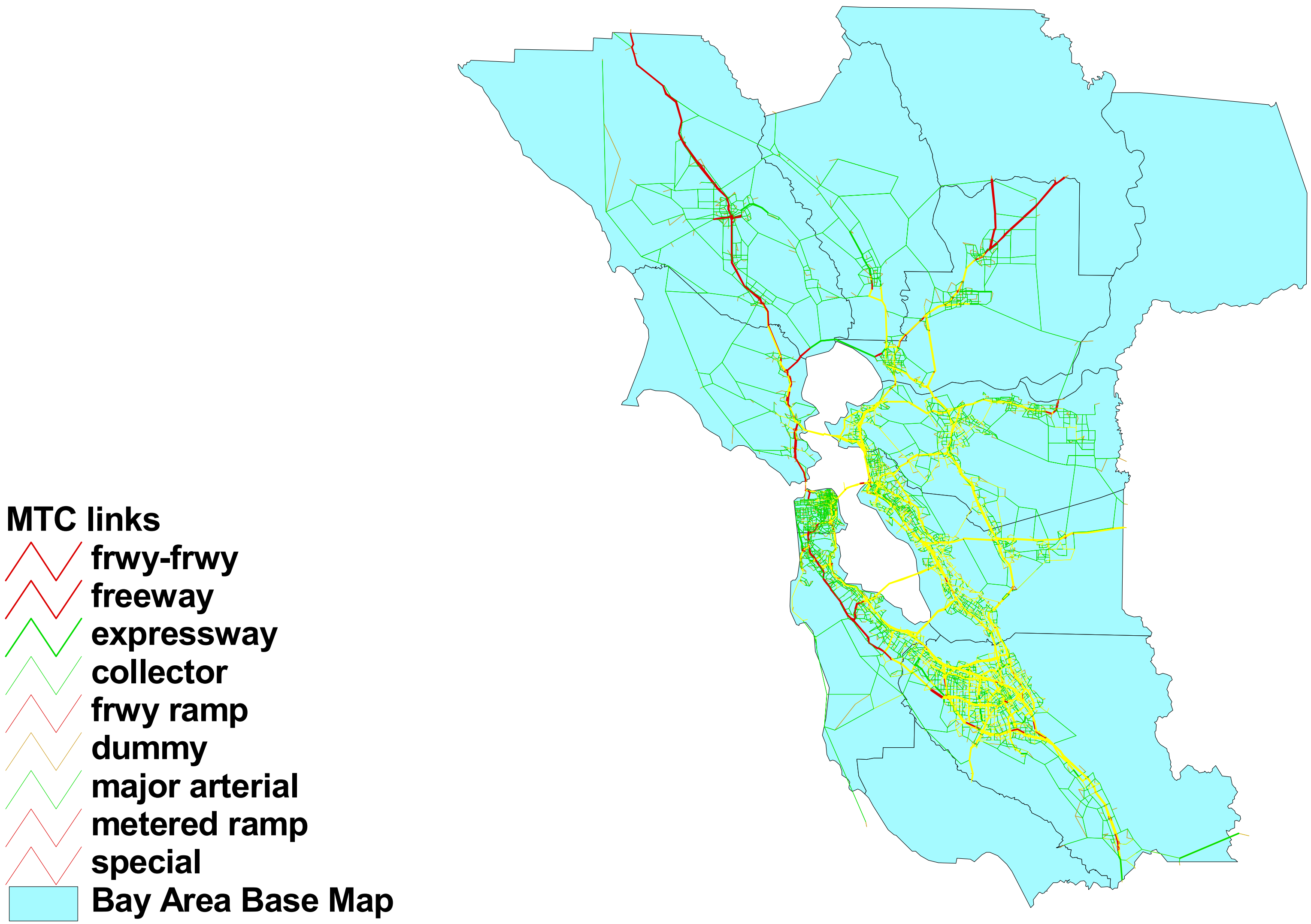
Proportionate Difference in Trip Production, Variable vs. Fixed Demand



Comparison between Base and Hayward 7.5 Scenarios - Links with Increased Volume



Comparison between Base and Hayward 7.5 Scenarios - Links with Decreased Volume



What is required to succeed fully in the case of the managing seismic risks to the transportation system?

- The first step in using this kind model to develop is to predict system performance following an earthquake. Post event, the benefits of any feasible reconstruction sequence can then be computed from the corresponding sequence of improvements in system performance. Net benefits are determined by comparing this sequence of improvements to the cost of reconstruction. Evaluating retrofit options is more difficult, because of the uncertainty of earthquakes.

- One way to approach this research challenge is to treat retrofit reconstruction decisions as a large-scale transportation network design problem. This is a difficult class of problems. Conventional approaches to these problems combine mathematical programming with bi-level control or implicit enumeration techniques.

- Even these techniques may be difficult to apply to metropolitan area models. Following a major earthquake, the feasible set of reconstruction sequences is likely to be too large to be tractable.

The Deterministic Transportation Network Design Problem: Link Addition (L. LeBlanc)

- Subject to budget (and possibly other) constraints, find the transportation network configuration on which user equilibrium flows produce the least total congestion.
- Given: link projects indexed on $i = 1, \ldots, m$,
  existing (remaining) links indexed on $i = m+1, \ldots, n$
  c_i = (re)construction cost of project i
  B = (re)construction budget constraint
- Define: x_i = the flow x on link i indexed 1, …, n,
  x_i^s = the flow x on link i indexed 1, …, n, and with destination s indexed 1, …, p
  $A_i(x_i)$ = the average travel time on link i as a function of flow x.
  $T_i(x_i)$ = the total travel time on link i as a function of flow $x = x_i \bullet A_i(x_i)$
  D(j, s) = the (fixed) demand for travel from node j to destination s
  $U = \{u_1, \ldots, u_m \mid u_i = 0, 1\}$
  M = an arbitrarily large number greater than the capacity of any link i

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$$\min_{u_i \in U} \; T(x^*) = \sum_{i=1}^{n} T_i(x_i^*) = T\left[\operatorname{argmin} \sum_{i=1}^{n} \int_0^{\sum_{s=1}^{p} x_i^s} A_i(t)\, dt\right]$$

Subject to: $\sum c_i \bullet u_i \leq B$

$\sum_{s=1}^{p} x_i^s \leq M \bullet u_i$ all i = 1, …, m

$\sum_{s=1}^{p} x_i^s \leq M(1 - u_i)$ all k and i such that project i improves link k

$D(j, s) + \sum_{\substack{\text{links } i \\ \text{inbound to } j}} x_i^s = \sum_{\substack{\text{links } i \\ \text{outbound from } j}} x_i^s$ all nodes j, all destinations s = 1, …, p

$x_i^s \geq 0$ all i = 1, …, n, all s = 1, …, p

$u_i = 0, 1$ all i = 1, …, n

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- The deterministic version of the problem is an embedded optimization problem with a bi-level structure.
    - The upper level is a the decision by the network authority, represented in LeBlanc's formulation as the addition of capacity.
    - The lower level, a function of the upper level decision, is the decision by the network user, represented in LeBlanc's formulation only as a route decision.
- The deterministic problem is typically formulated as a bi-level control problem or an implicit enumeration (branch and bound) problem at which a nonlinear programming problem is solved at each node in a branch and bound tree.
- Explicit enumeration would be a prohibitively expensive way to solve even a modestly sized problem.
- Post-event network reconstruction problems are large-scale network design problems.
    - Collectively, the intra-urban work to date sponsored by PEER, MCEER, and NSF provides support for prioritizing and sequencing post-event reconstruction projects.
    - The inter-urban work to date at MAE suggests more of a pre-event perspective.

The Stochastic Transportation Network Design Problem: Performance of Degraded Networks (M. Bell)

- Subject to budget (and possibly other) constraints, find the transportation network configuration on which user equilibrium flows produce the least expected total congestion.
- The stochastic version of the problem is an embedded optimization problem with a tri-level structure.
  - The upper level is a the decision by the network authority, in this case a pre-event retrofit or reconstruction decision.
  - The intermediate level outcome, a function of the upper level decision, is a random result of nature.
  - The lower level, a function of the upper level decision and the intermediate outcome, is the decision by the network user.
- Explicit enumeration of options is out of the question. A network with M links presents 2^M retrofit options. A random act of nature converts the network to a collection of $L < M$ links. The total number of possible networks to be considered is thus $\sum_L {}_M C_L \bullet 2^L$.